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High Temperature Latent Heat Thermal Energy Storage to Augment Solar Thermal Propulsion for Microsatellites

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THE AIR FORCE RESEARCH LABORATORY
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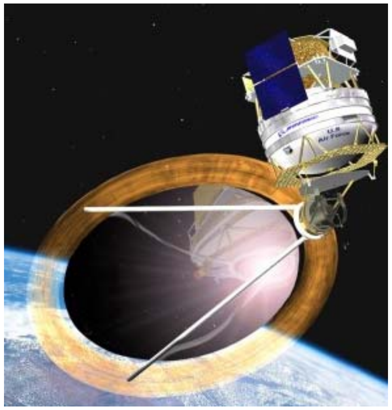
Introduction

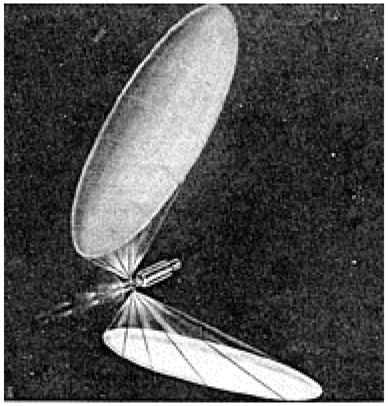
- Solar thermal propulsion (STP) has over 50 years of developmental history and offers a compromise between thrust and efficiency

- No solar thermal spacecraft have been flown
  - Complicated architecture
  - System scale
  - Adverse mission impact

- It is proposed here that a bi-modal solar thermal microsatellite has the potential to greatly increase the operating envelope of the platform

- The development of high temperature latent heat thermal energy storage is currently an enabling technology





Presentation Outline

1. Solar Thermal Propulsion Overview
   - Technological History
   - Developmental Milestones
2. Bi-modal Solar Thermal Microsatellite
   - Technological Requirements
   - Phase Change Material Selection
   - Performance Evaluation
3. Proposed Study
4. Current Work / Results
   - USC Solar Furnace
   - Materials Studies
   - Modeling Capability
   - Experimental Results
5. Future Work & Project Conclusions

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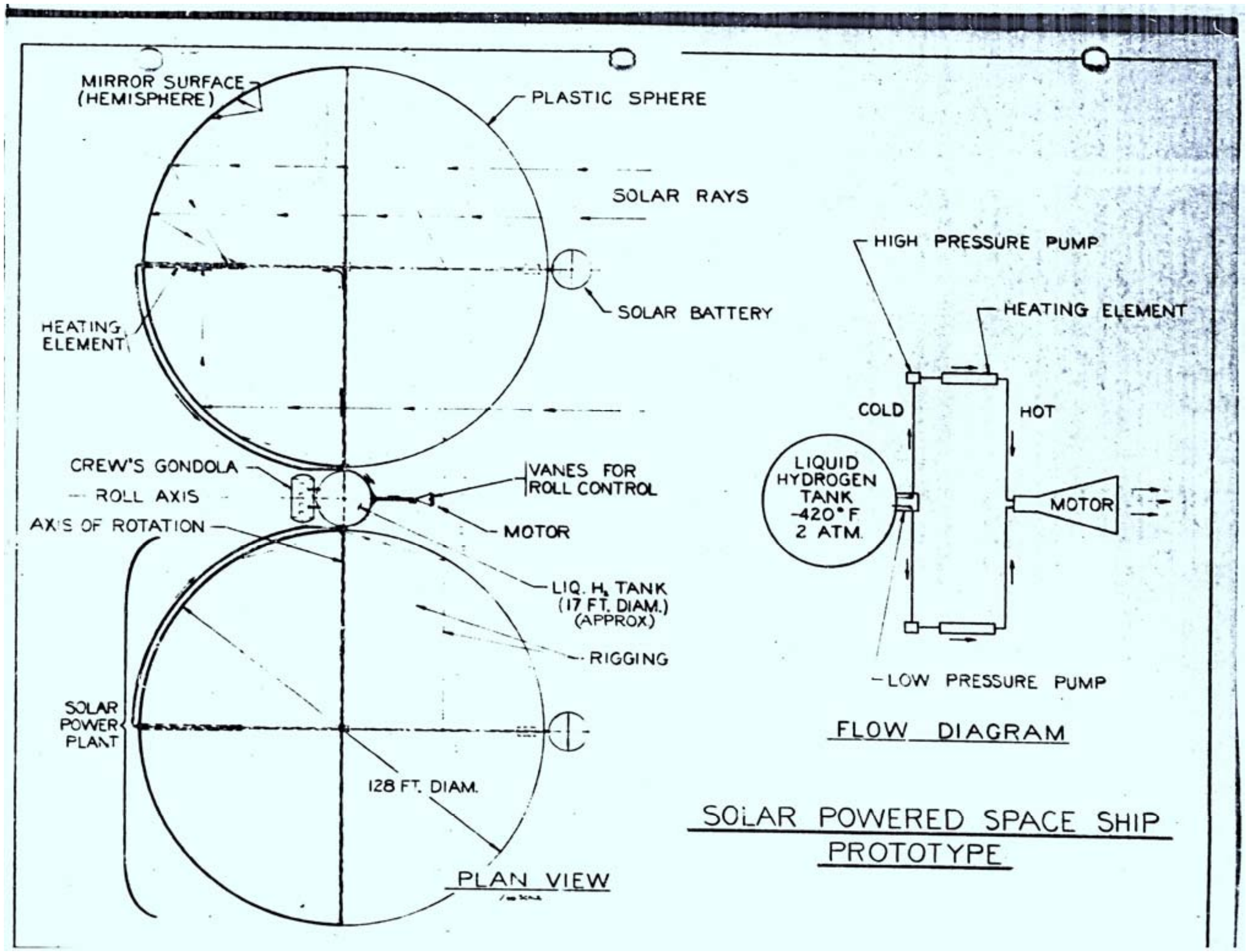
Solar Thermal Propulsion Overview

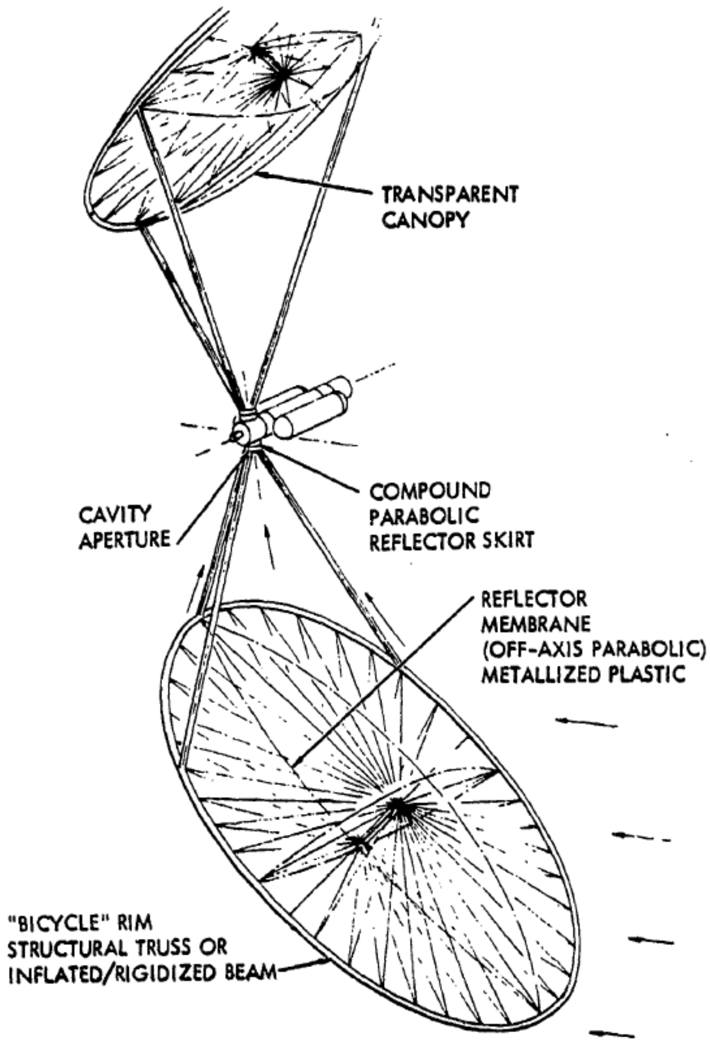
1956 — 1980s — 1990s — 2000s — Today



- "Solar Powered Space Ship" proposed by Krafft Ehricke
- 7500 *kg* spacecraft with a two man crew
- AFRPL funded investigation at Electro-Optical Systems (EOS) in 1963 produced solar heated H_2 at approx. 2300 K
- Work halted due to concerns about "awkward" vehicle design and integration issues
- Funding was shifted to a competing advanced concept

Solar Thermal Propulsion Overview

1956 | 1980s | 1990s | 2000s | Today



- Space Shuttle – “represents a national commitment to extended operations in space” *Selph 1981*
- 1979 Rockwell report, funded through AFRPL, concludes a solar thermal rocket is possible and recommends near term production
- Vehicle integration was greatly simplified by a centrally located solar receiver and inflatable concentrators
- Compared performance of **28,100 *kg***, shuttle launched spacecraft for LEO-GEO transfer

Engine Type	LO_2-H_2	Ion	Solar 1	Solar 2
ΔV (*m/s*)	4,270	5,850	5,850	4,800
Isp (*sec*)	475	2,940	872	872
Trip Time (*days*)	5	180	14	40
Payload to Geo (*kg*)	9,250	20,000	9,300	13,200

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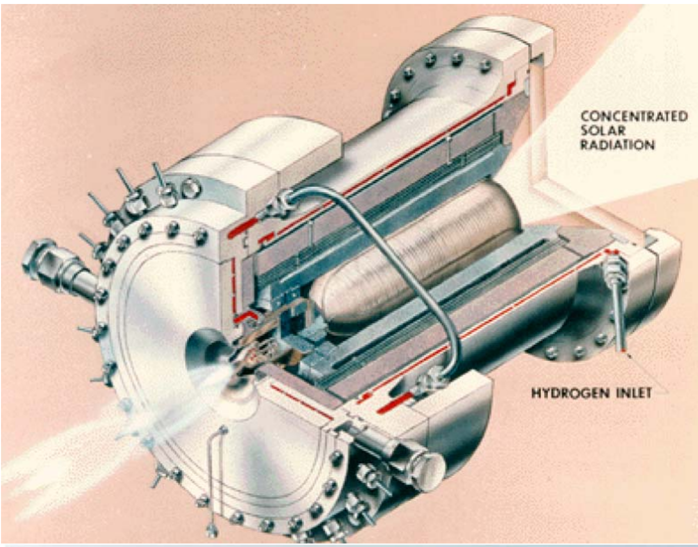
Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today



- AFRPL funded effort for experimental demonstration based on findings of Rockwell report
- Rocketdyne contracted to produce a solar thermal thruster using coiled rhenium tubing with a target exit temperature of 2705 *K*
- Solar furnace problems limited testing temperatures to approximately 1800 *K*
- AFRPL declared technology “feasible” but development was slowed in 1989 due to budget cut-backs
- Note that the design **does not** include a means of thermal energy storage

“…time spent traversing the Earth shadow results in a trip-time increase of approximately 10% at no increase in propellant expended.”
Ethridge 1979

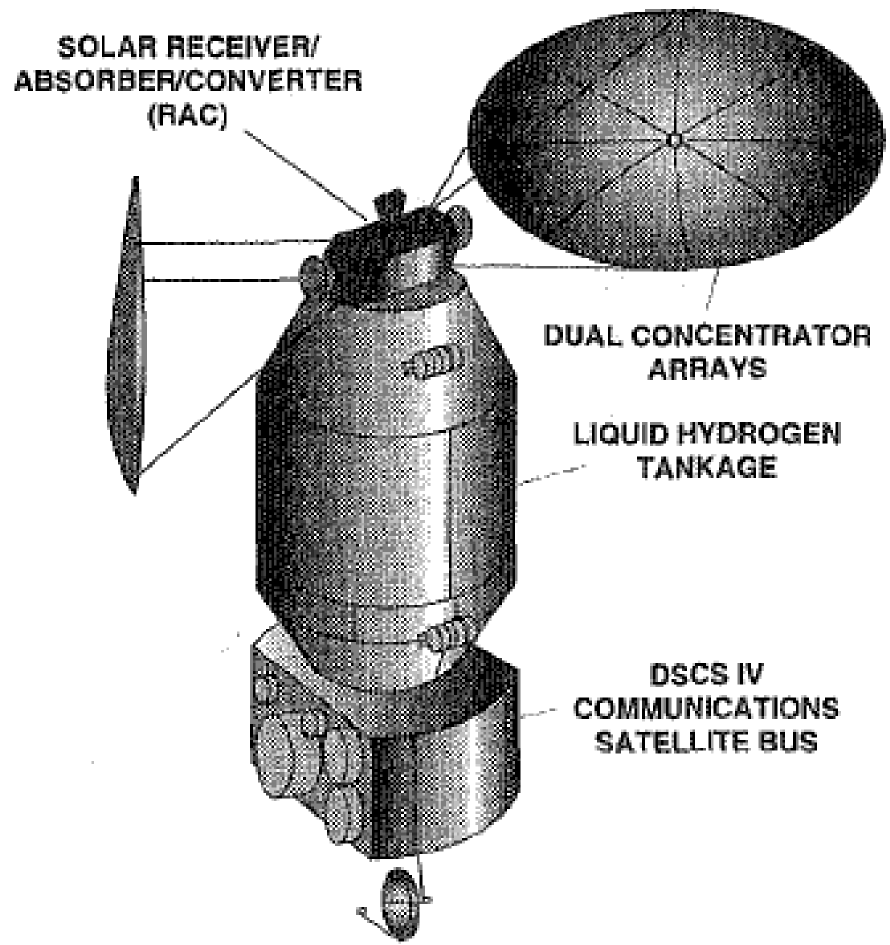
Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today

- A **bi-modal** nuclear thermal system capable of providing propulsive and electrical power was proposed in the early 1990s
- Integrated upper stage design supplies electrical power to the payload after orbit transfer
- Reduced mass: potential for launch vehicle "step down"

Delta II 7925	Titan IIG
\$50M in 1995	\$18-30M in 1995
1800 kg to GTO	1000 kg to GTO

- Due to waning interest in nuclear thermal research, AFRPL considered the concept with a solar thermal architecture
- Sought to quickly reduce the cost of Air Force space operations using *existing* technology



Solar Thermal Propulsion Overview

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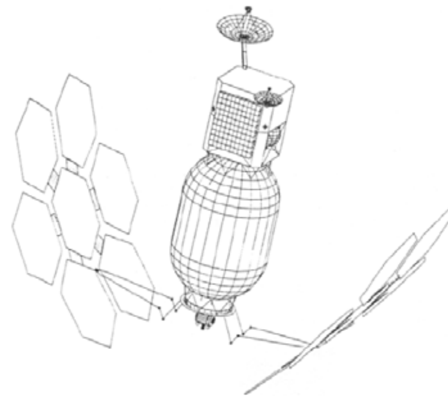
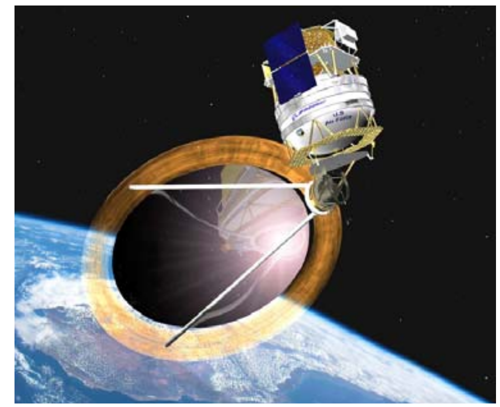
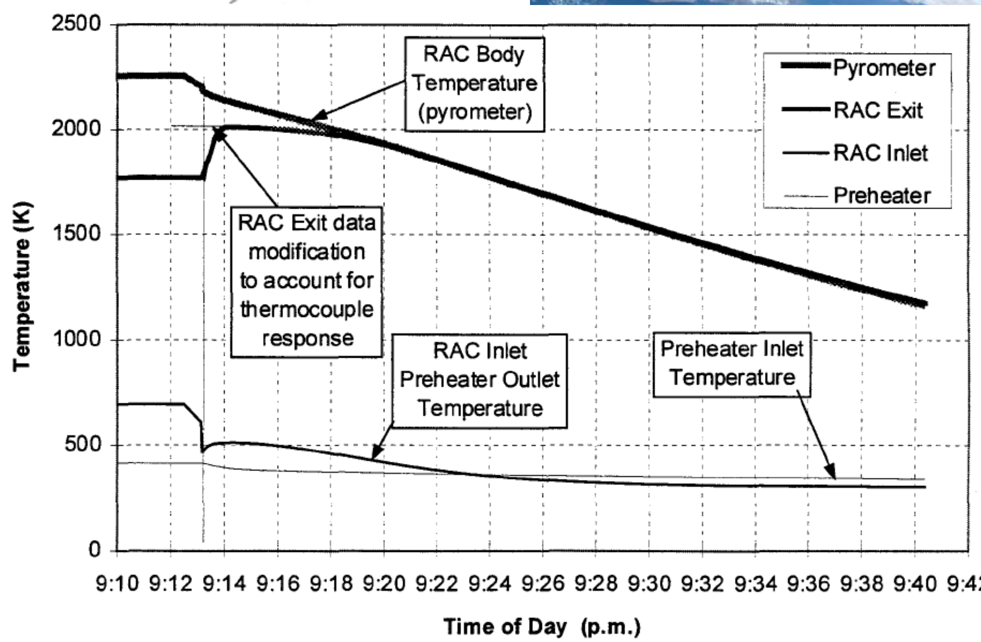
1956 — 1980s — **1990s** — 2000s — Today

- Integrated Solar Upper Stage Program (ISUS) initiated in 1994
- ISUS program targeted a “militarily” useful payload on orbit by 1998 – *very optimistic*
- Performed a ground test of a prototype Receiver-Absorber-Converter (RAC)
- RAC incorporated sensible heat thermal energy storage – necessitated by the bi-modal design
- Succeeded in recording data for hot flow hydrogen testing
- Program closed in 1998 – followed by Boeing Solar Orbit Transfer Vehicle (SOTV) and the STP Critical Flight Experiment at NASA Marshall







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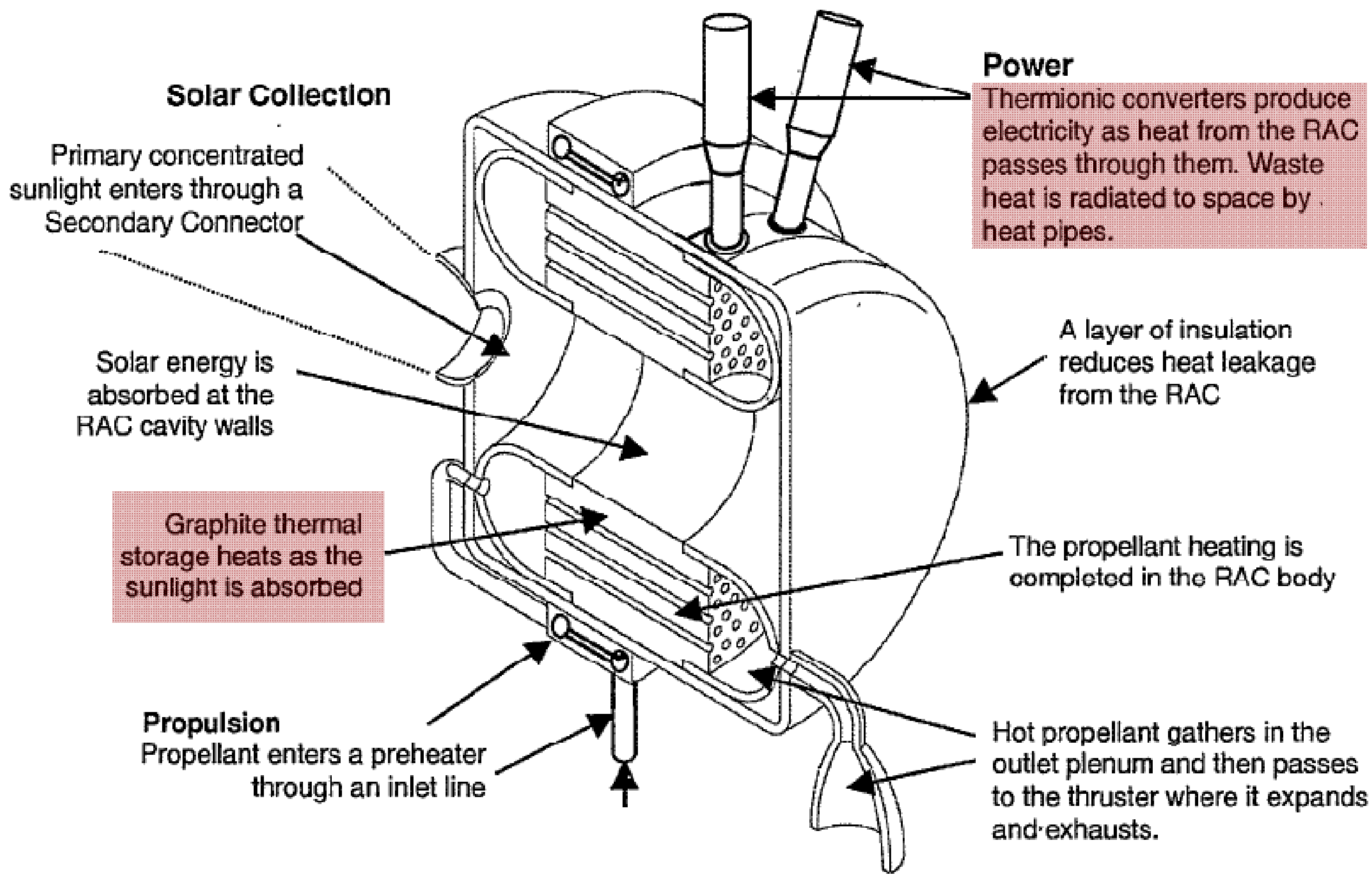
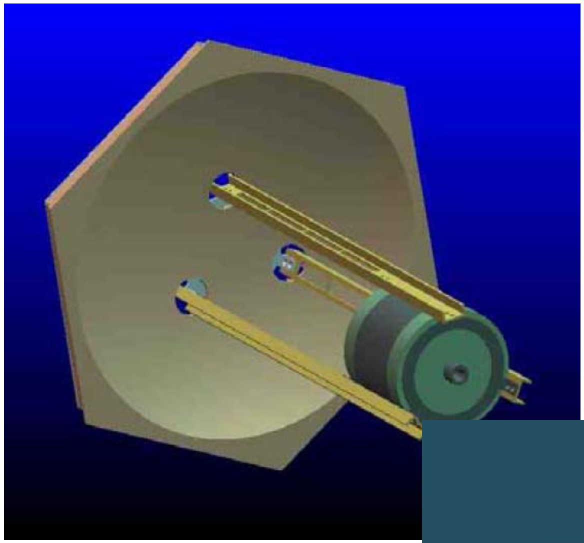
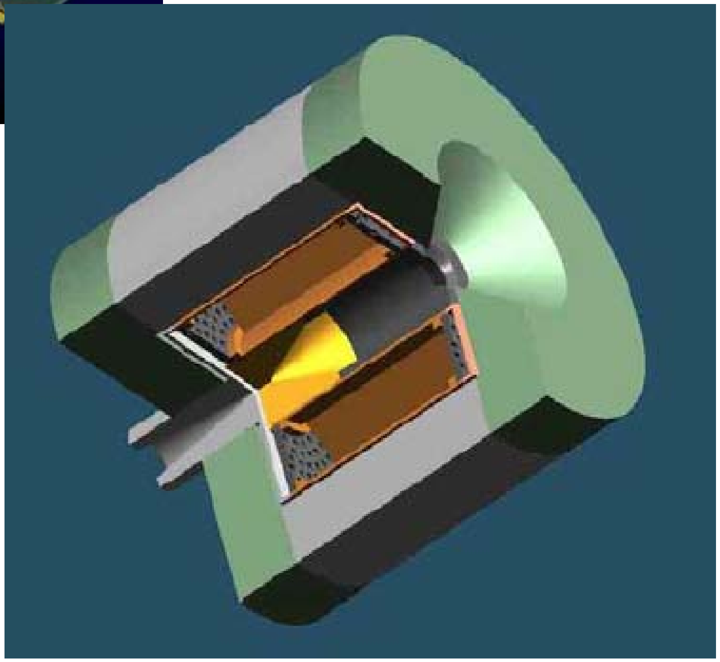


Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today

- Concept shifted to microsatellites (10-100 kg) in an effort to *finally* mount a space demonstration
- Project headed by Kennedy, a veteran of the ISUS program, at Surrey Space Center
- Proposed the use of non-cryogenic propellants such as N_2H_4 and NH_3 and "packed bed" sensible heat thermal energy storage
- Achieved experimental NH_3 temperatures approaching 2000 K
- Other small scale research efforts
  - Thin film concentrator and Mo receiver work at JAXA
  - Fiber optic coupling work at Physical Sciences Inc





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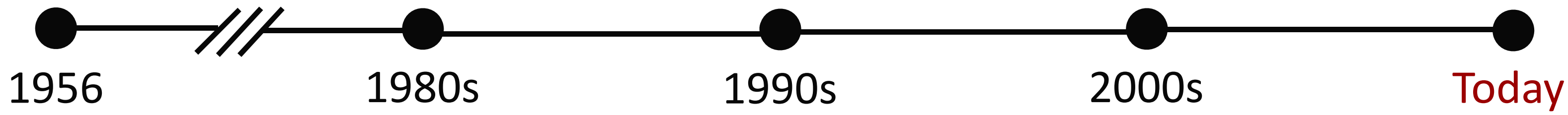
Solar Thermal Propulsion Overview

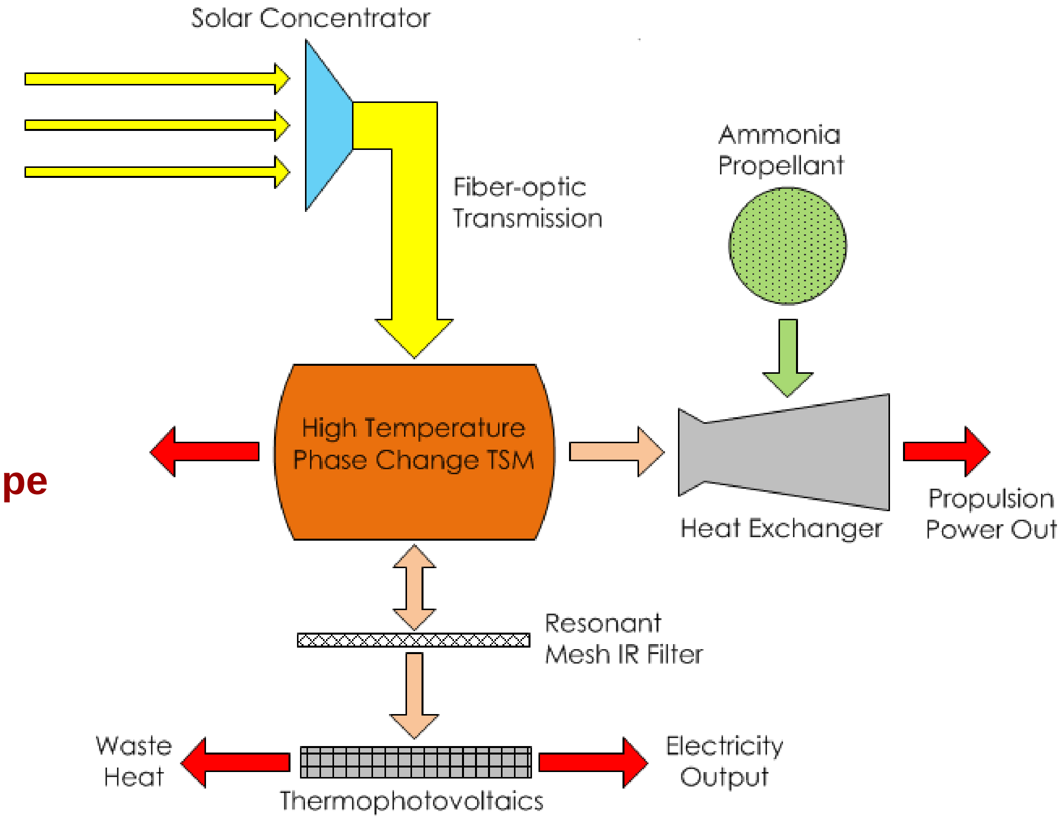


- Drawing from Kennedy's microsatellite study, a review by the AFRL advanced concepts group identified STP as a promising candidate for high performance microsatellite missions
- A ***bi-modal microsatellite*** configuration is proposed and further study is recommended
- Microsatellite scaling distinguishes STP
- Large ΔV (> 1 km/s) possible

Expand the Microsatellite Operating Envelope

- Expand possible "piggy-back" launch options
- GEO Insertion: *~ 1760 m/s*
- Near Escape Missions: ~ *770 – 1770 m/s*

Possible with EP, however, STP offers a much shorter burn time and higher maneuverability



Technological Requirements

☐ Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☐ Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

☐ Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

☐ Advanced Insulation

- Low Mass
- High Temperature

☐ High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

☐ Compatible / Effective RAC

- Long term compatibility
- Effective energy coupling

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- Thin PMA (JAXA) "flight ready" concentrators achieve 200 g/m^2 and C. ratios > 10,000:1
- Inflatables (AFRL, SRS) can achieve < 1 kg/ m^2 and have been reported as being "optical quality"
- Large rigid structures (NASA SD, ISUS) are listed at approx. 3 kg/ m^2 including mounting, tracking, and deployment
- Microsatellite scale system only requires < 2 m^2

Sahara 2004

SRS Technologies

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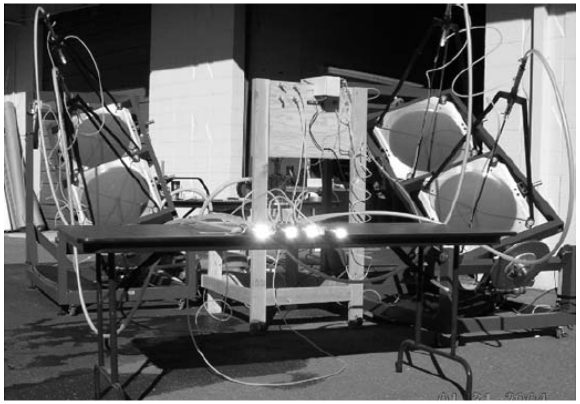
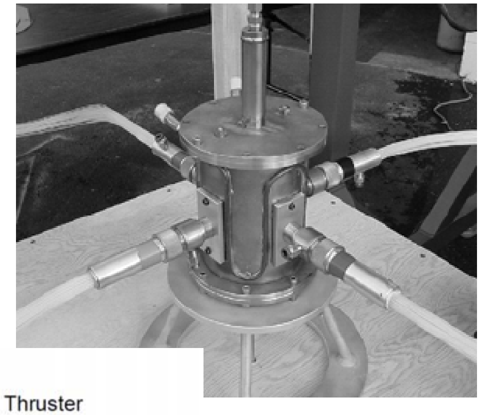
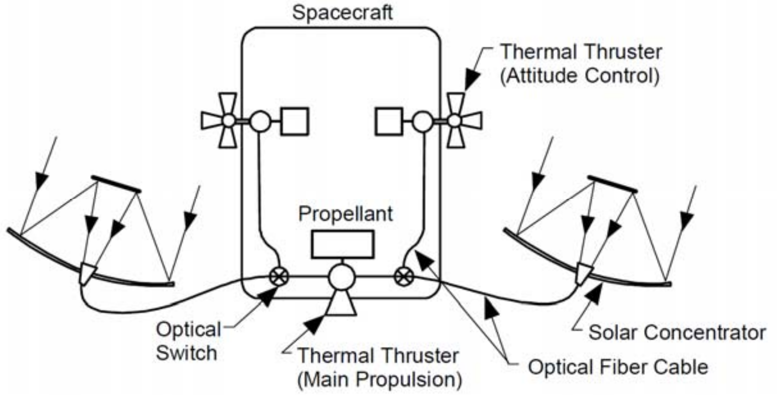
- Current lab systems operate at 35% η_{total}
- Estimated 70% η_{total} for a space qualified system from better materials selection
- Pointing accuracy of approx. 0.1° required



Nakamura 2004





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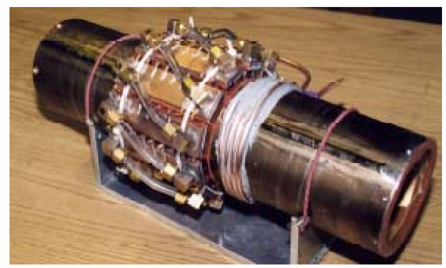
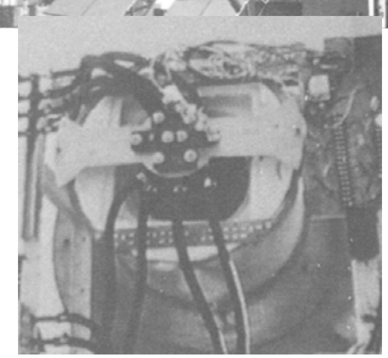
- Thermophotovoltaics are the strongest candidate
- Operation targets properly matched to solar thermal temperatures.
- 15 W/kg in current systems, including radiator
- Closed Brayton and thermionics scale poorly for microsats

Edtek



McDonnell Douglas



Technological Requirements

USC Viterbi School of Engineering

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- High Temperature

☐ High Temperature Storage Material

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- High energy density (> 1000+ kJ/Kg)

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- Long term compatibility
- Effective energy coupling

Material	k_{th} @ 1000 C *(W/mK)*	k_{th} @ 1500 C *(W/mK)*	k_{th} @ 2000 C *(W/mK)*	Density *(g/cm3)*
Silicon Carbide	45	30	*25*	3.2
Boron Nitride	17-33	22.5	*18*	1.8
Alumina	6.5	6.6	--	3.8
Zirconia	2	2.5	*3*	5.5
ONRL CBCF	0.17	0.2	0.26	0.2
Calcarb CBCF	0.2	0.35	0.65	0.18
Aerogel Filled Graphite Foams	0.25	0.4	0.75	0.07
Mo - $Zr0_2$ Multifoil	0.001	0.05	0.1	1.4

- Must operate between **1500 – 2600** K
- **Carbon Bonded Carbon Fiber**
  - Can draw from NASA RTG development
  - Carbon foams with filler to limit radiation loss currently offered by ULTRAMET
- **Low Emissivity Vacuum Gap**
  - Typically the first stage in a TPV system
  - Mo/ZrO_2 multifoil blankets also produced for RTGs
- **Ceramic Doped Aerogels**
  - Underdevelopment with JPL, RZSM, and RQRS

Technological Requirements

Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

Advanced Insulation

- Low Mass
- High Temperature

High Temperature Storage Material → ?

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

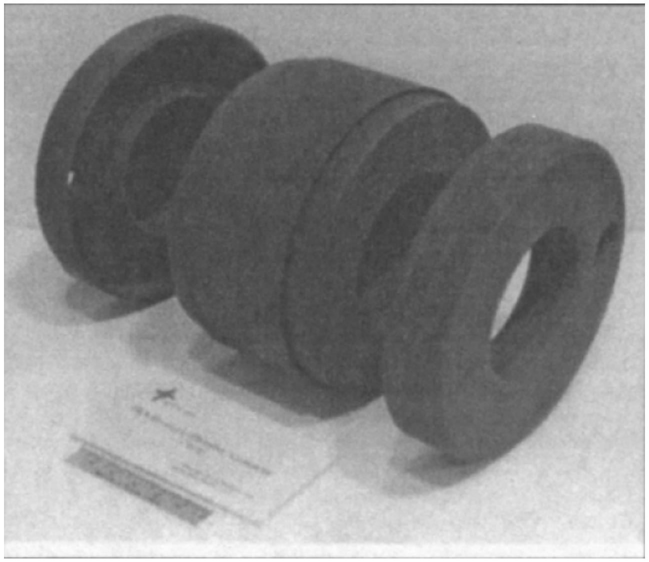
Compatible / Effective RAC → ?

- Long term compatibility
- Effective energy coupling

Existing Sensible Heat Thermal Energy Storage

To date, all STP systems have used sensible heat thermal energy storage

Material	T_{melt} [K]	Cp @ 2500 K [kj/kgK]	ΔT Required for 1 MJ/kg
Grahpite	3923	2.15	475
Boron Carbide	2700	2.68	380
Silicon Carbide	2818	1.01	740
Boron Nitride	3273	1.98	510



- Simplified engineering suitable for time constrained development – Low TRL level of other options
- "…moderate yet acceptable performance" - *Kennedy 2002*

ISUS Data Analysis

- Seven minute "steady" burn corresponds to an "effective" energy storage density of **0.5 *MJ/kg***
- When the RAC achieves 1 *MJ/kg*, ***exit temp*** has dropped by ***> 25%*** and ***Isp*** has dropped by ***15%***
- ISUS spec for thermionic hot shoe temperature was 1900 – 2200 K. If allowed for a radiatively coupled TPV system, this would correspond to a ***> 50% decrease*** in power output

Terrestrial Phase Change Materials

Class	T_{melt} [K]	ΔH_{fus} [MJ/kg]	k_{th} [W/mK]
Paraffin Wax	317 – 379	0.072 – 0.214	0.19 – 0.75
Fatty Acids	268 – 344	0.045 – 0.210	0.14 – 0.17
Hydrated Salts	281 – 1170	0.115 – 0.492	0.46 – 5.0

- Energy density and k_{th} an order of magnitude too low
- Melt temperatures too slow for STP
- Decomposition after repeated cycling

Terrestrial Phase Change Materials

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Hydrated Salts	281 – 1170	0.115 – 0.492	0.46 – 5.0

Potential High-Temp Phase Change Materials

Material	T_{melt} [K]	ΔH_{fus} [MJ/kg]	k_{th} @ Tmelt [W/mK]
MgF2	1536	0.94	3.8
Beryllium	1560	1.31	*69*
Silicon	1687	1.79	20
Nickel	1728	0.3	*83*
Scandium	1814	0.31	*16*
Chromium	2180	0.4	48
Vanandium	2183	0.45	51
Boron	2350	4.6	*10*
Ruthenium	2607	0.38	*80*
Niobium	2750	0.29	*82*
Molybdenum	2896	375	*84*

Latent Heat Thermal Energy Storage

Terrestrial Phase Change Materials

Class	T_{melt} [K]	ΔH_{fus} [MJ/kg]	k_{th} [W/mK]
Paraffin Wax	317 – 379	0.072 – 0.214	0.19 – 0.75
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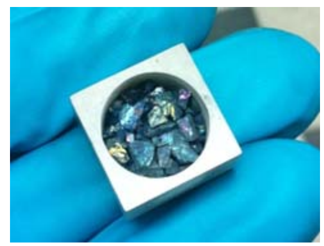
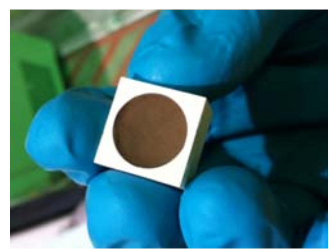
Molybdenum	2896	.38	*84*

Silicon



- Moderate Performance
- 330s I_{sp}

Boron



- High Performance
- 390s I_{sp}

System Comparison

Bi-Modal System Performance Parameters

100 *kg* Microsatellite - 100 *W* continuous power draw

Silicon System		
Thermal Collection	5.3	*kg*
Thermal Storage	3.3	*kg*
Power	6.7	*kg*
Propellant	36.7	*kg*
Tankage / Thruster	6.1	*kg*
Prop. / Power Total	**58.2**	***kg***
Payload Mass	**41.8**	***kg***

$M_{\text{Propulsion \& Power}}$ ~ 58%

1500 *m/s* *ΔV*

Thermal Collection
- Primary concentrator
- Support structure
- Fiber optics

Thermal Storage
- PCM
- Insulation

Power
- TPV cells
- Radiator Panels

Propellant
- Liquid Ammonia

Tankage / Thruster
- Titanium Tank
- Piping
- Nozzle and Heat Exchanger
- Reinforcements

System Comparison

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100 *kg* Microsatellite - 100 *W* continuous power draw

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$M_{\text{Propulsion \& Power}}$ ~ 58%

1500 m/s ΔV

Boron System		
Thermal Collection	5.4	*kg*
Thermal Storage	1.9	*kg*
Power	6.7	*kg*
Propellant	38.0	*kg*
Tankage / Thruster	6.3	*kg*
Prop. / Power Total	**58.2**	***kg***
Payload Mass	**41.8**	***kg***

$M_{\text{Propulsion \& Power}}$ ~ 58%

1850 m/s ΔV

Thermal Collection
- Primary concentrator
- Support structure
- Fiber optics

Thermal Storage
- PCM
- Insulation

Power
- TPV cells
- Radiator Panels

Propellant
- Liquid Ammonia

Tankage / Thruster
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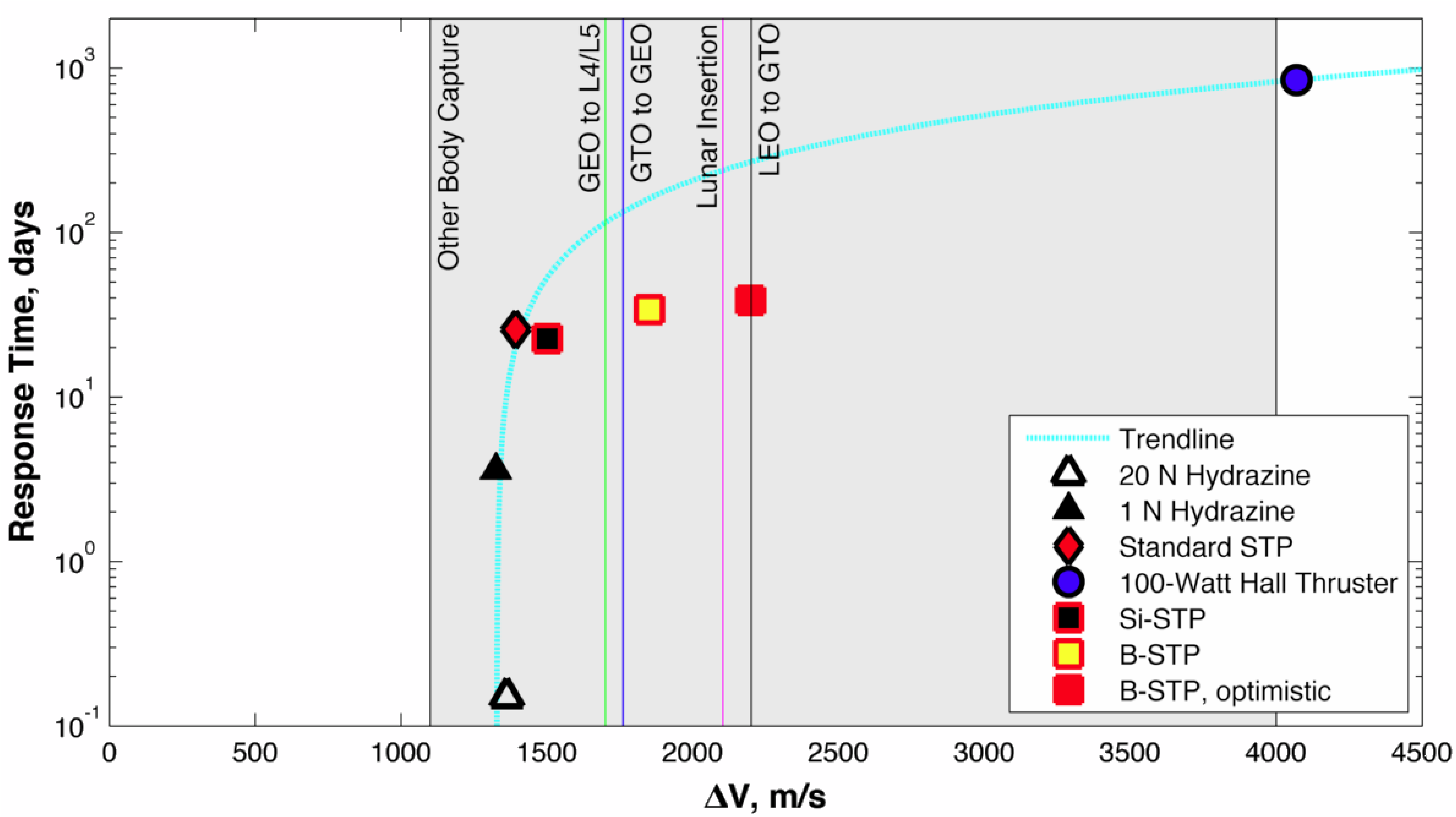
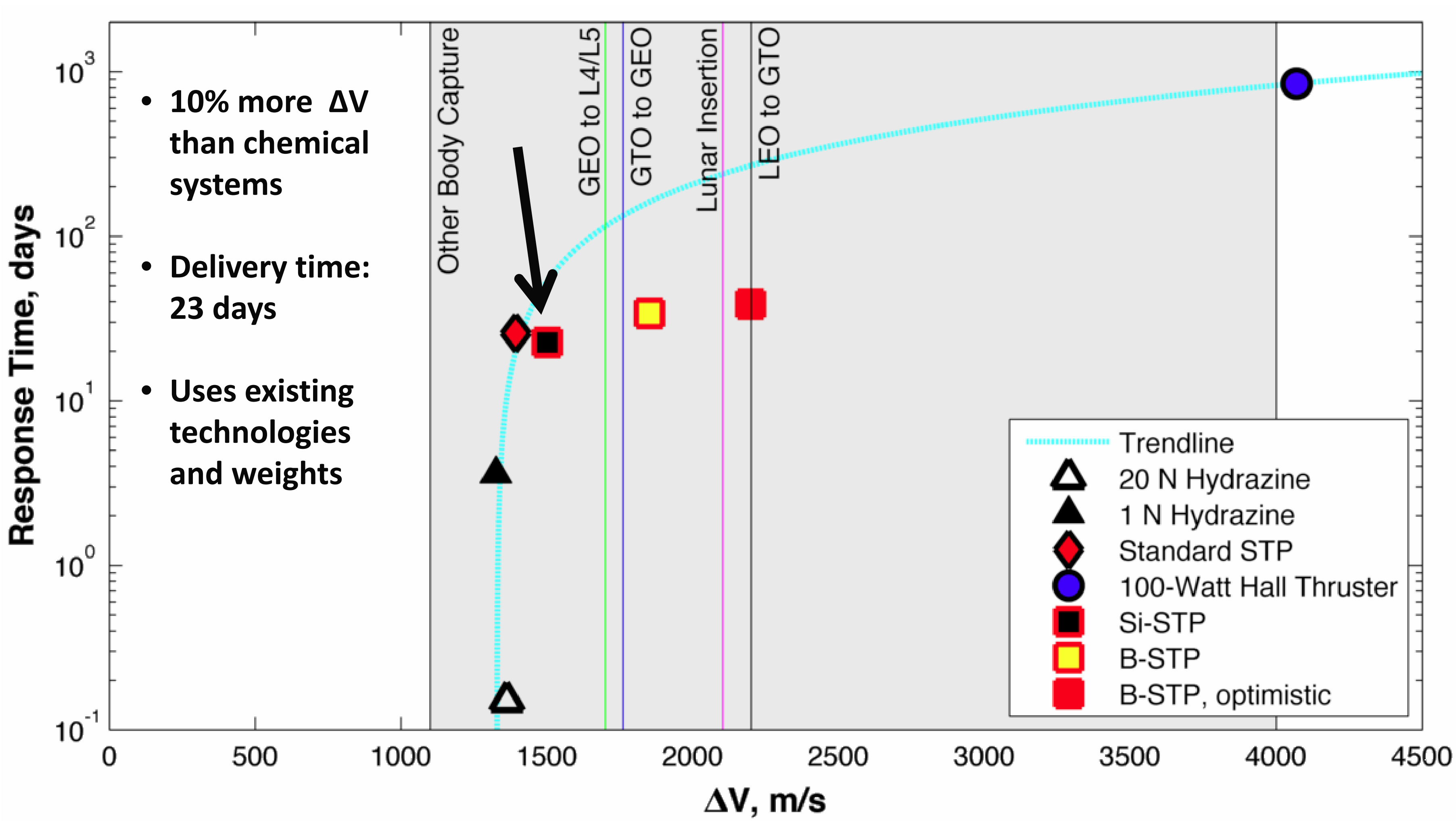
System Comparison



System Comparison

- **10% more ΔV than chemical systems**
- **Delivery time: 23 days**
- **Uses existing technologies and weights**



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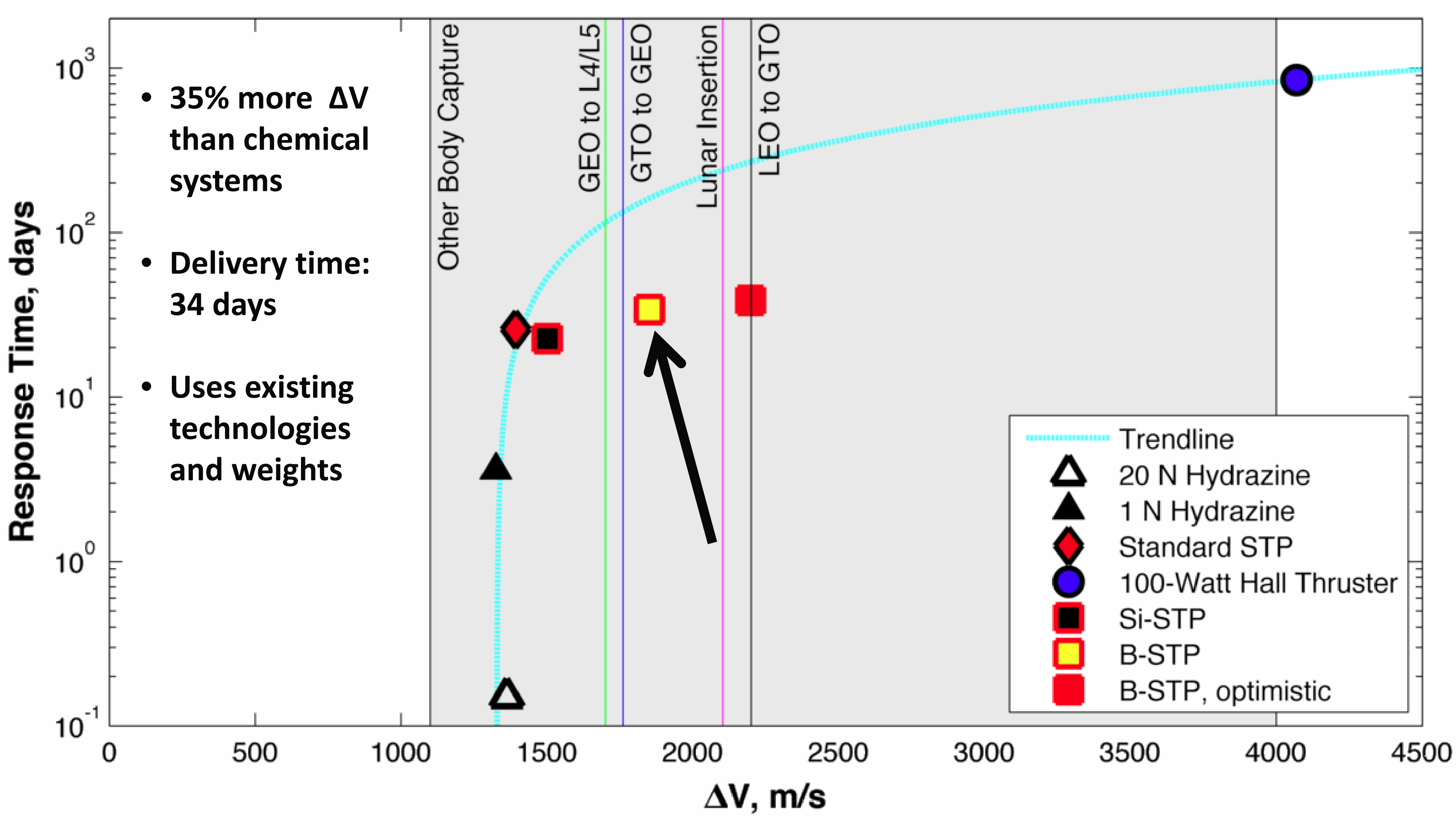
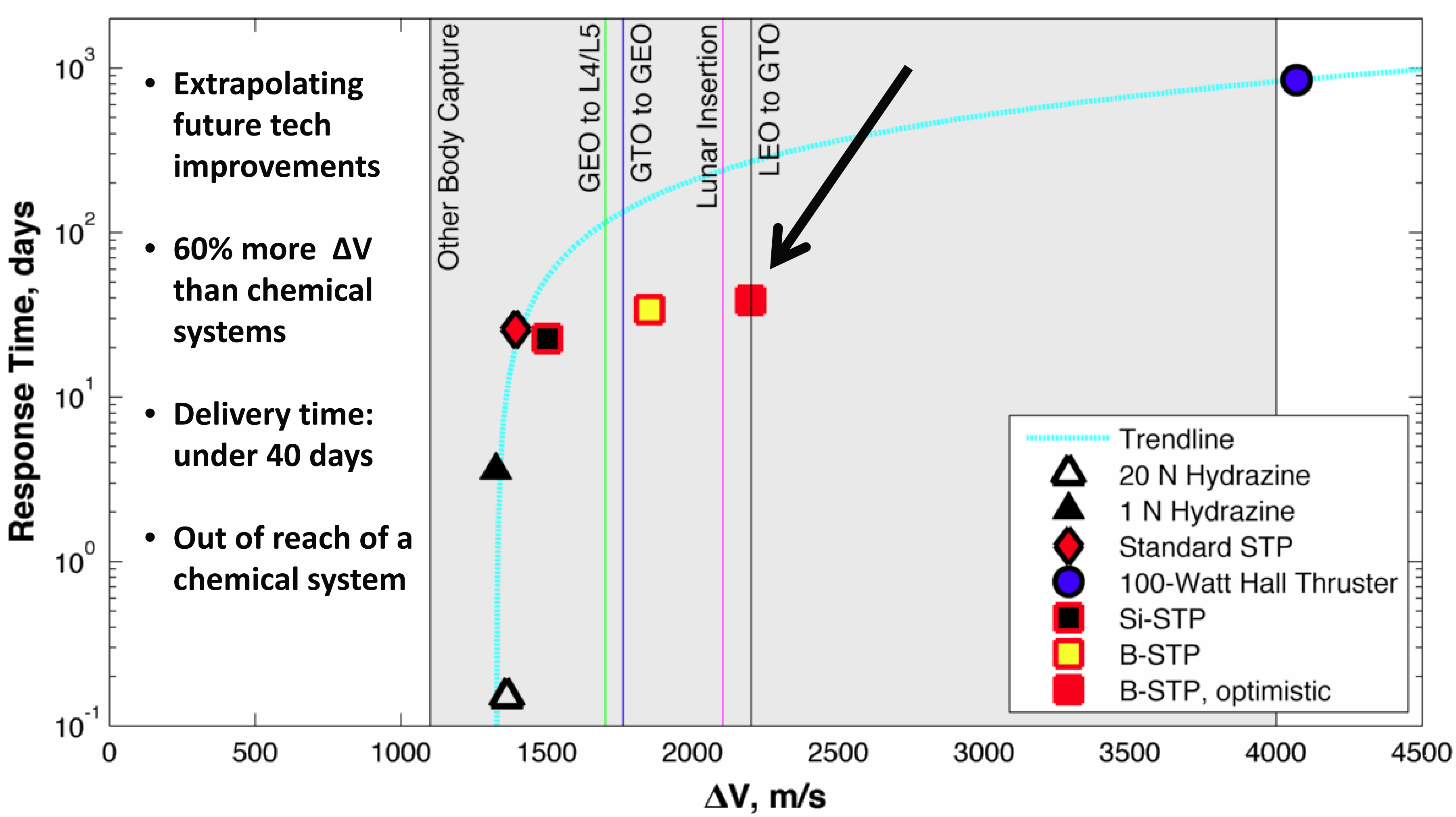
System Comparison

- **35% more ΔV than chemical systems**
- **Delivery time: 34 days**
- **Uses existing technologies and weights**



System Comparison

- **Extrapolating future tech improvements**
- **60% more ΔV than chemical systems**
- **Delivery time: under 40 days**
- **Out of reach of a chemical system**



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Existing Knowledge

Silicon

- **Mentioned as a potential buffer / storage material for TPVs**
  - ➢ Woodall 1982 - IBM patent
  - ➢ Chubb et al. 1996 - white paper, "ideal storage material"
- **Brief mentions in the solar thermal literature**
  - ➢ Laug et al. 1995 – Initial bi-modal study
  - ➢ Kennedy 2002 – TRL level not sufficient
  - ➢ Abbot 2001 – Trade study
- **No experiments directly targeting energy storage applications**

Boron

- **Little knowledge of the material itself, let alone is use as an energy storage medium**
- **Existing experimental data is based on determining basic material properties**
  - ➢ 1960s-1970s – sealed container furnace experiments
  - ➢ 2000s – laser heated levitating drop experiments
- **Brief mentions in the solar thermal literature**
  - ➢ Shoji 1992 only considers weight savings from concentrator size reduction, says boron causes a net mass *increase*

Proposed Study

Experimentally Demonstrate a Proof of Concept Latent Heat Thermal Energy System Using Molten Silicon

1) Facility Development

- Design and build a solar furnace at USC capable of producing molten silicon samples
- Characterize the solar furnace for accurate flux maps and power output
- Ensures experimental correlation with future spacecraft system

2) Materials Selection

- Identify suitable container materials to resist attack from molten silicon and molten boron
- Container material must demonstrate long term stability

3) Modeling Capability and Analysis

- Develop sufficient modeling capability to predict experimental performance
- Asses the degrees of model fidelity required to capture essential system behaviors

4) Experimental Demonstration

- Experimental demonstration will identify practical concerns with molten silicon and boron
- Provide experimental data for concurrent multi-physics modeling work
- Goal is to emulate a single heat exchanger channel from the ISUS experiment and demonstrate convective coupling to a latent heat medium

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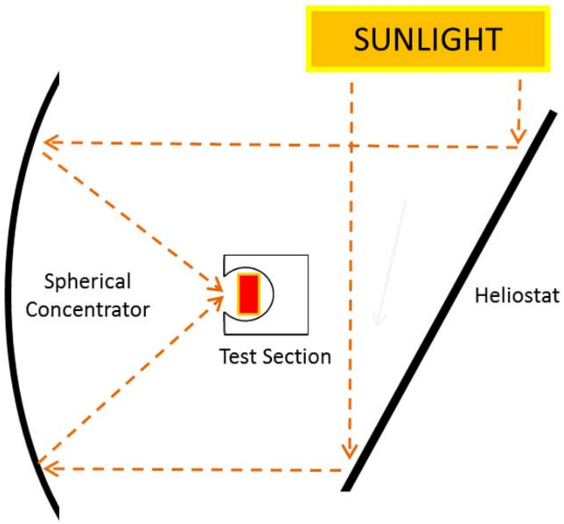
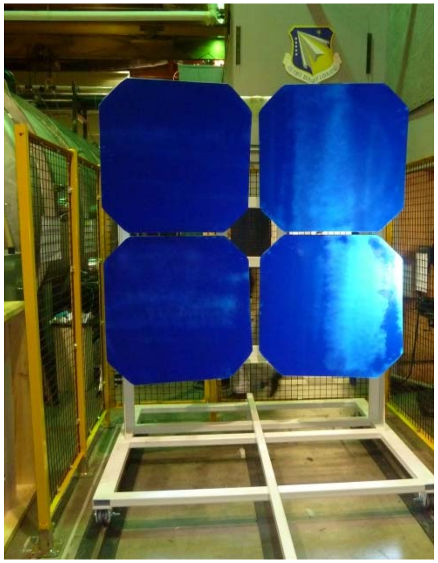
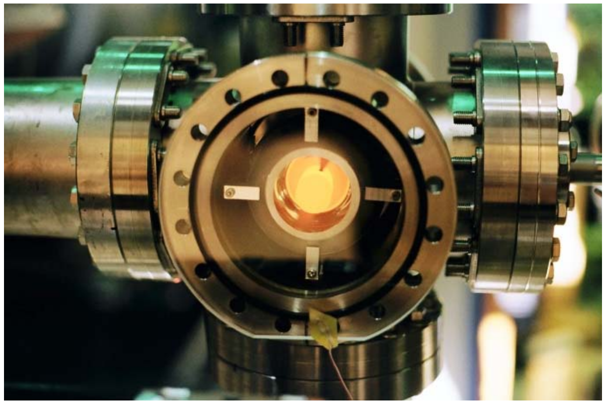
USC Solar Furnace

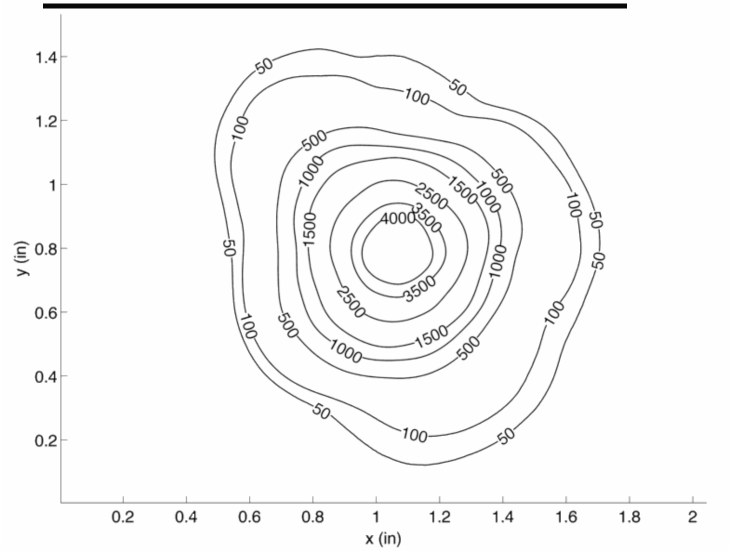
- First-surface spherical concentrator
  - r_c = 124”
  - SiO_2 coating optimized to the solar spectrum
  - Manufactured by DOTI Optics
- 3600 in^2 usable concentrator area
- 12 ft x 8 ft computer controlled heliostat
- COTS and surplus components
- Delivers 800-1100 W in a 1” spot

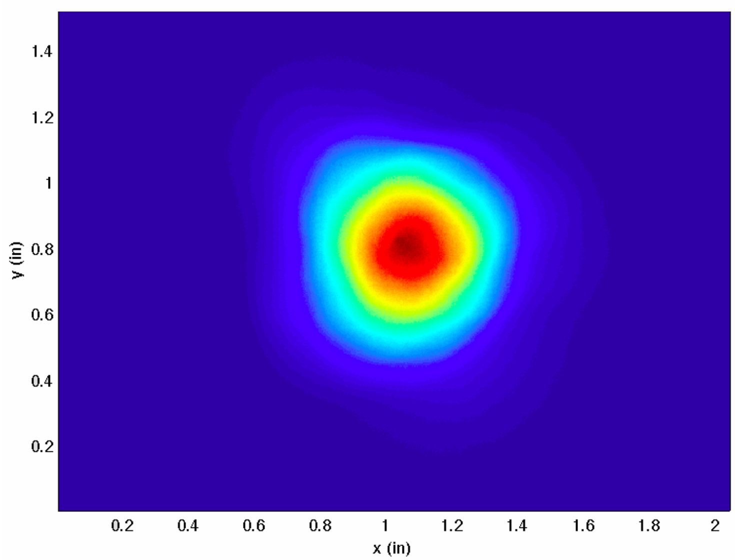




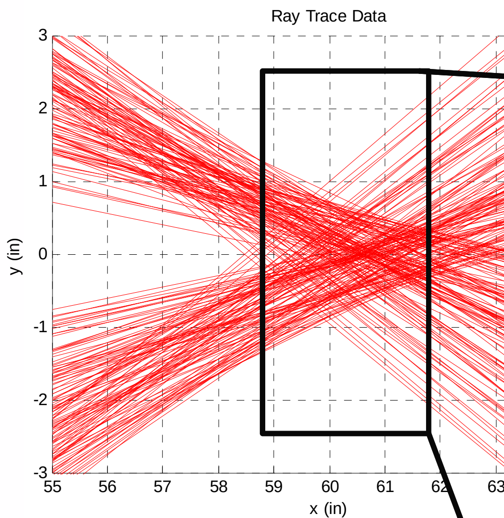


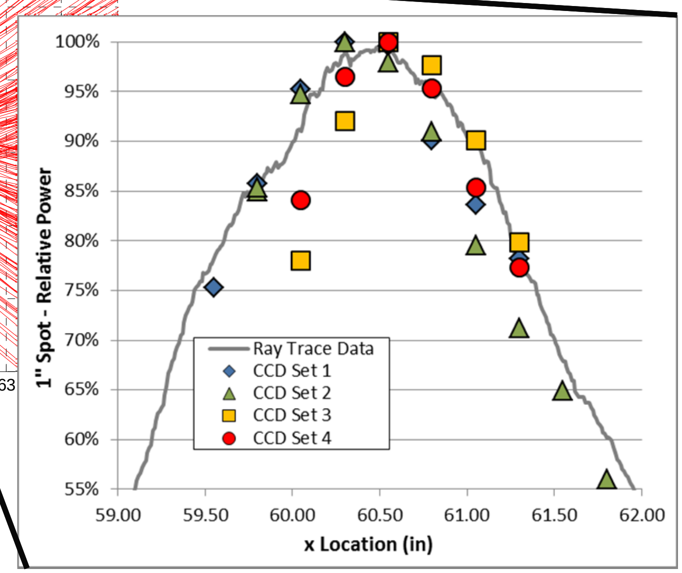
Solar Flux At Best Location





- Peak concentration ratios 4000:1
- Tailored for maximum power delivery in a 1” diameter spot
- Optimized experimental placement using CCD solar flux mapping to compensate for spherical aberrations



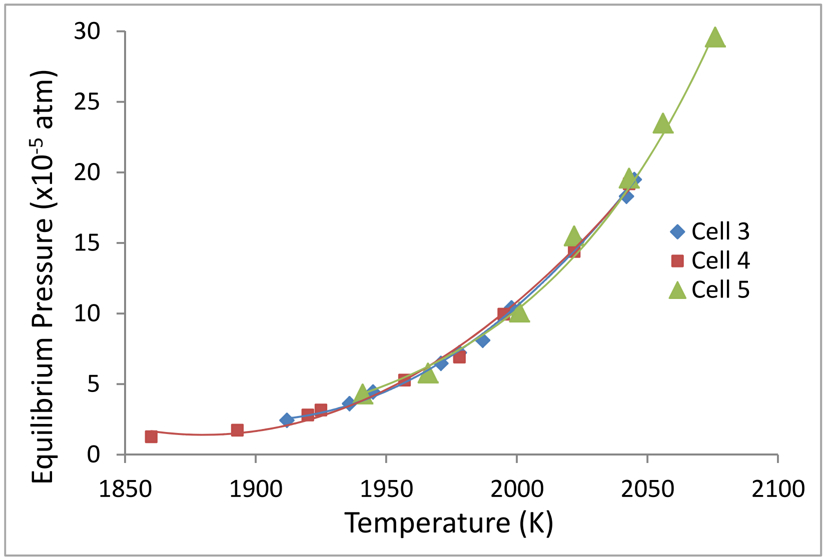


Geometric "Focus" :	62"
Minimum Ø :	59.8"
Best Performance :	60.5"

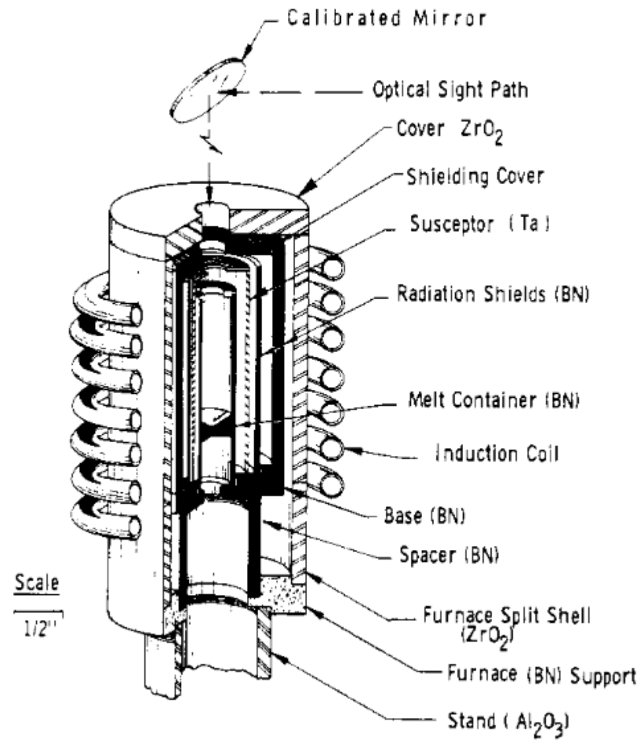
Materials Studies

Boron

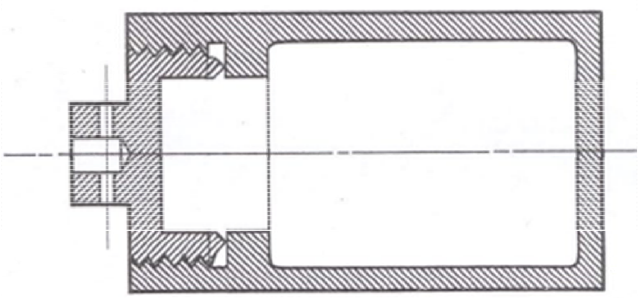
- Experimental data available for graphite, refractory metals, and boron nitride
- **Boron nitride** is suggested by the literature as the most promising container material
- Concerns about dissociation at high temperature. Approx. 7 Torr at 2350 K



Hildenbrand 1962



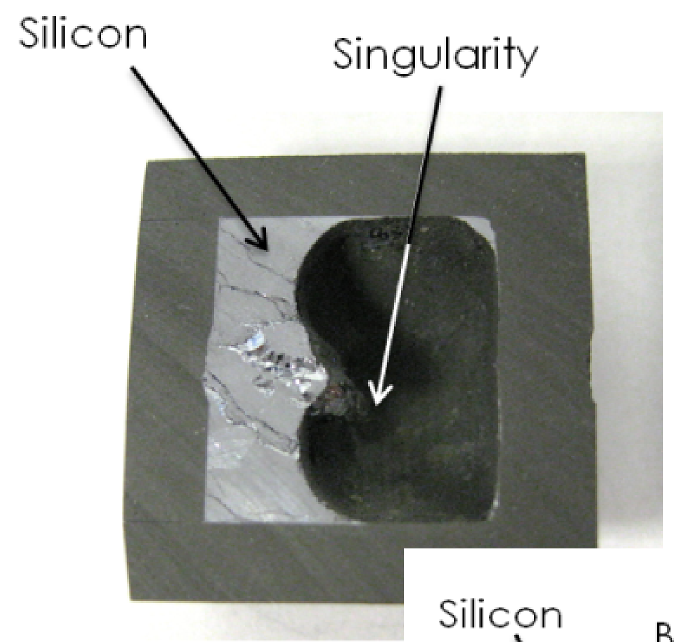
Kimpel & Moss 1968

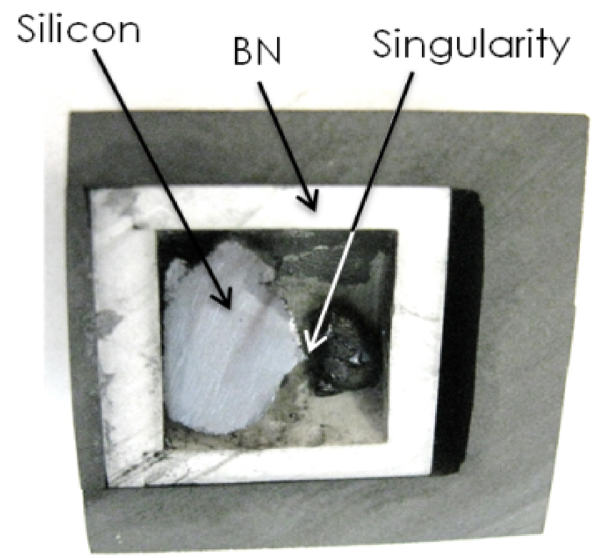


Stout et al. 1972

Silicon

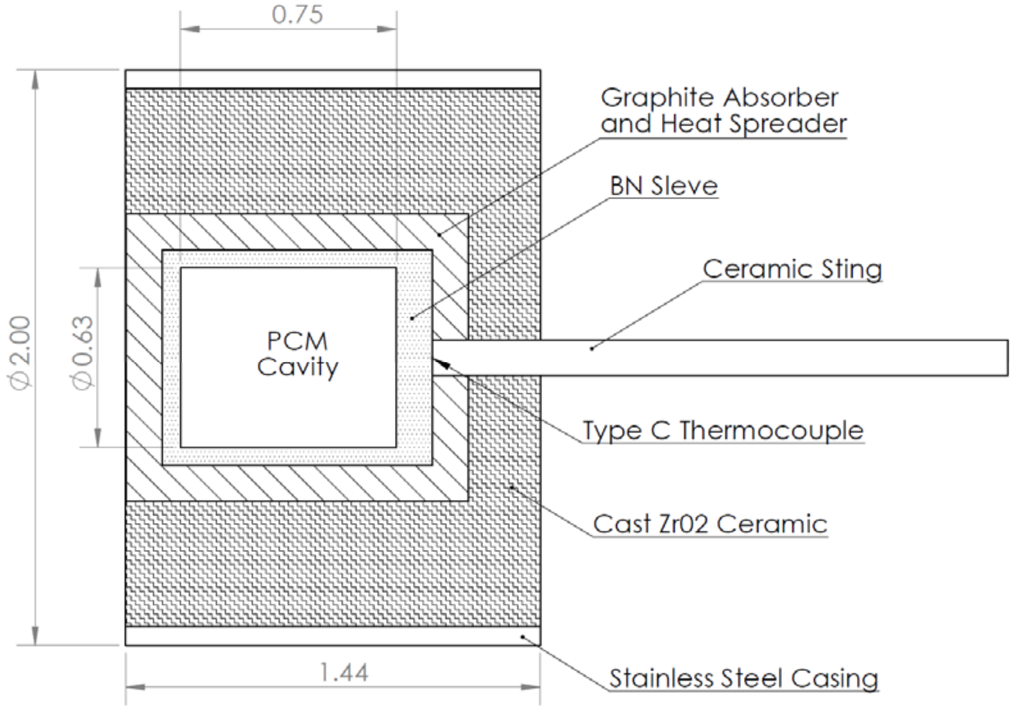
- Possible to draw from semi-conductor industry knowledge
- **Boron nitride** has a self limiting reaction with molten silicon
  - Formation of Si_3N_4 limited at 2% boron saturation in the silicon bulk
  - Low level boron contamination expected to have little effect on silicon recrystallization
- Graphite can be used with carbon contamination on the order of 20 ppm
  - Density must be > 1.75 g/cc
  - Grain size must be < 50 µm
- Approx. 10 % volumetric expansion during freezing process….



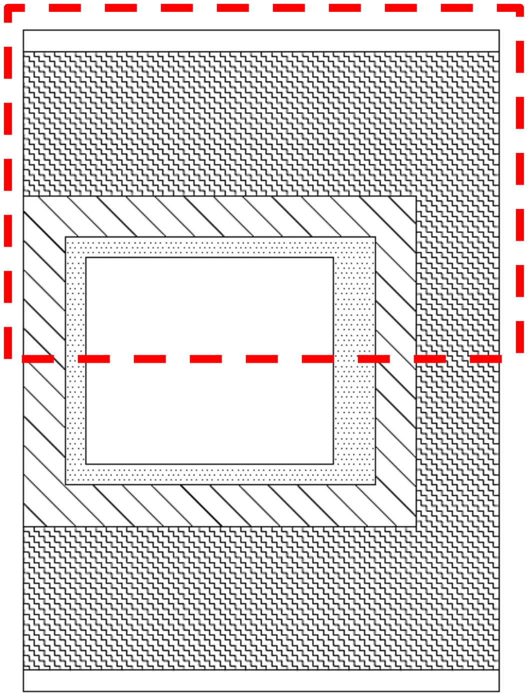


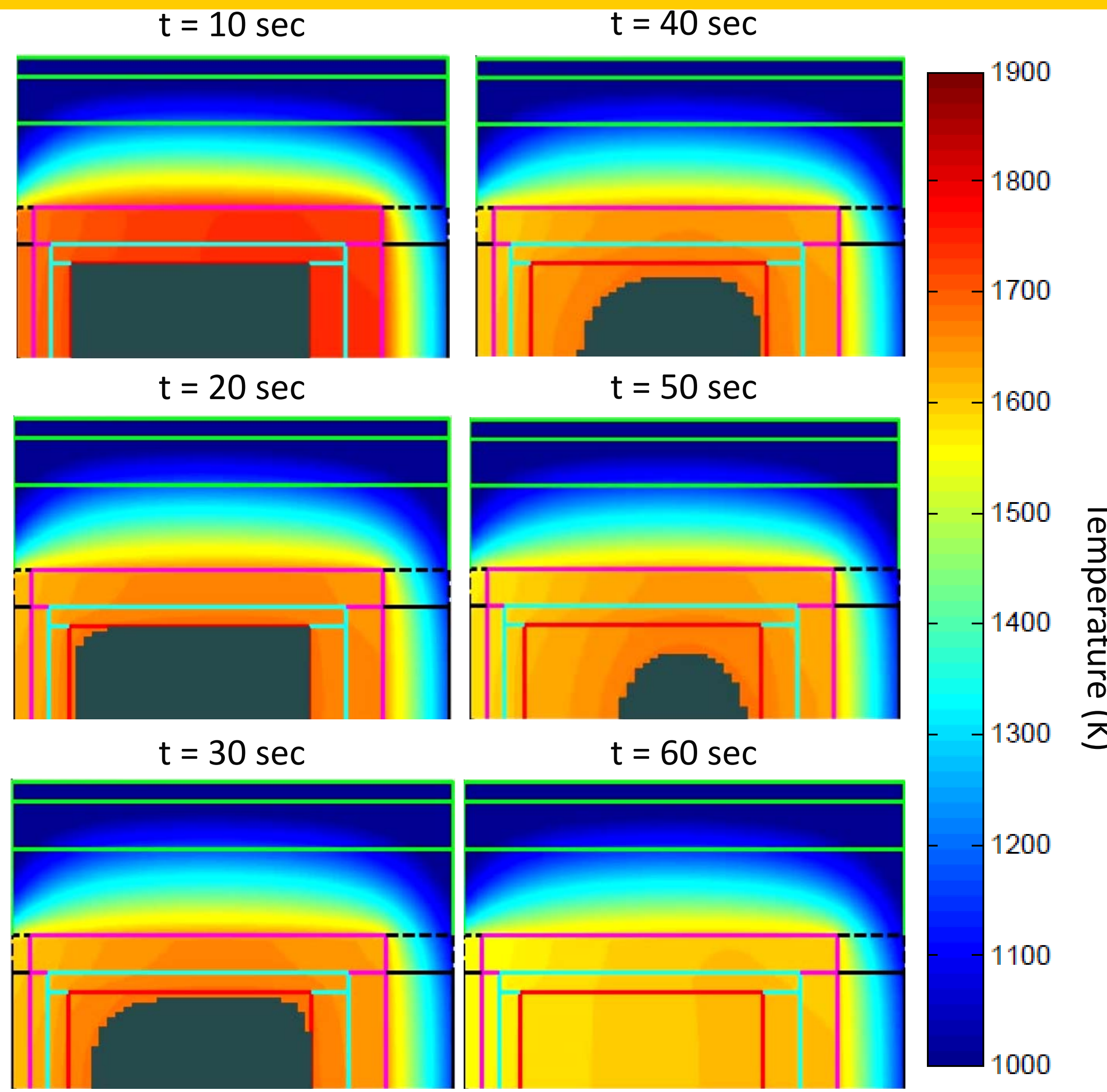
Testing Geometry

- Cylindrical geometry for ease of manufacture and simplified modeling
- Can be manufactured in house from COTS components
- Sized for 9 g of silicon, however, this is not limited by solar furnace power
- Does not make use of radiation shielding
- Integrated Type C and Type K thermocouples



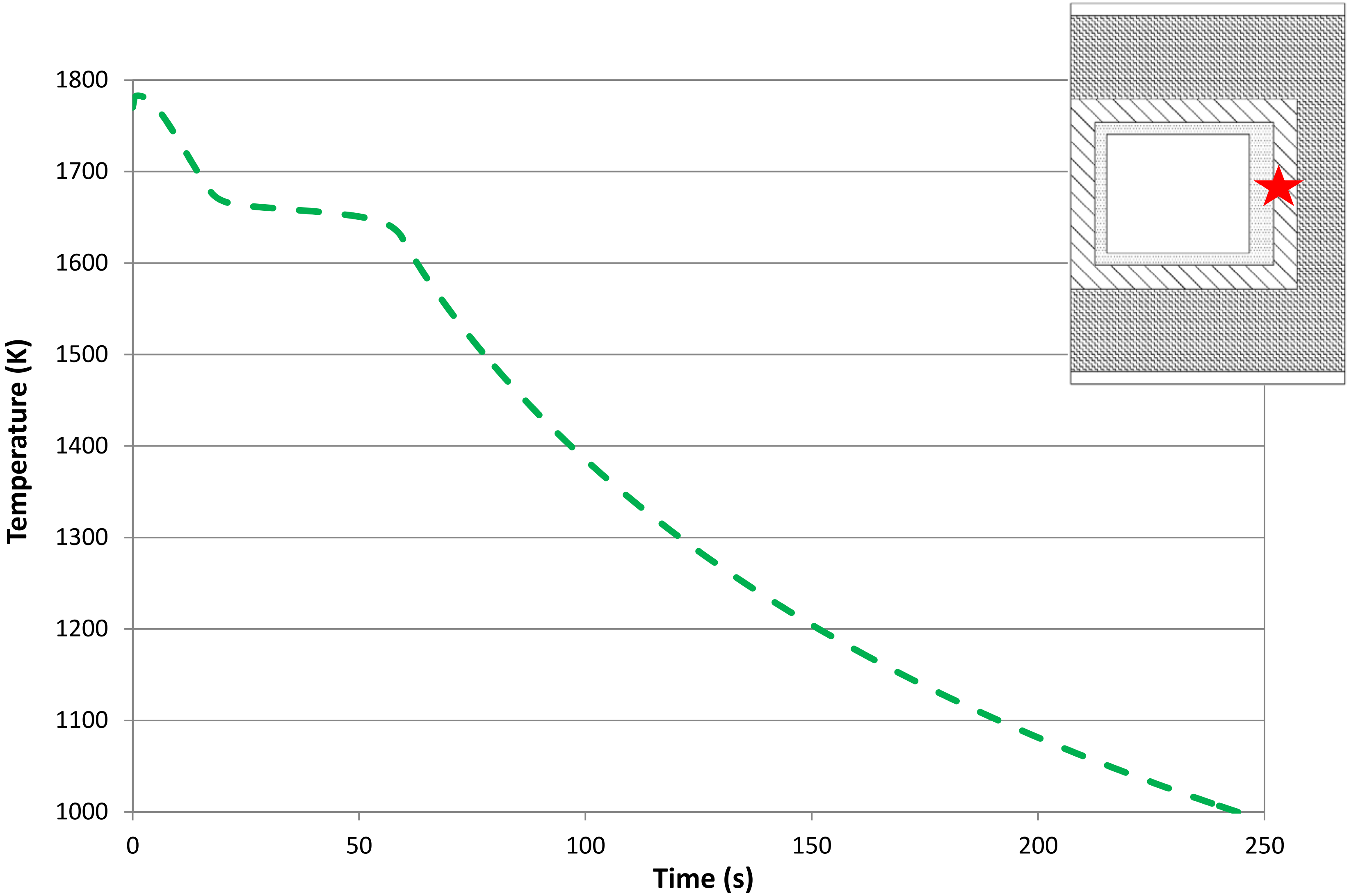
Predictive Modeling



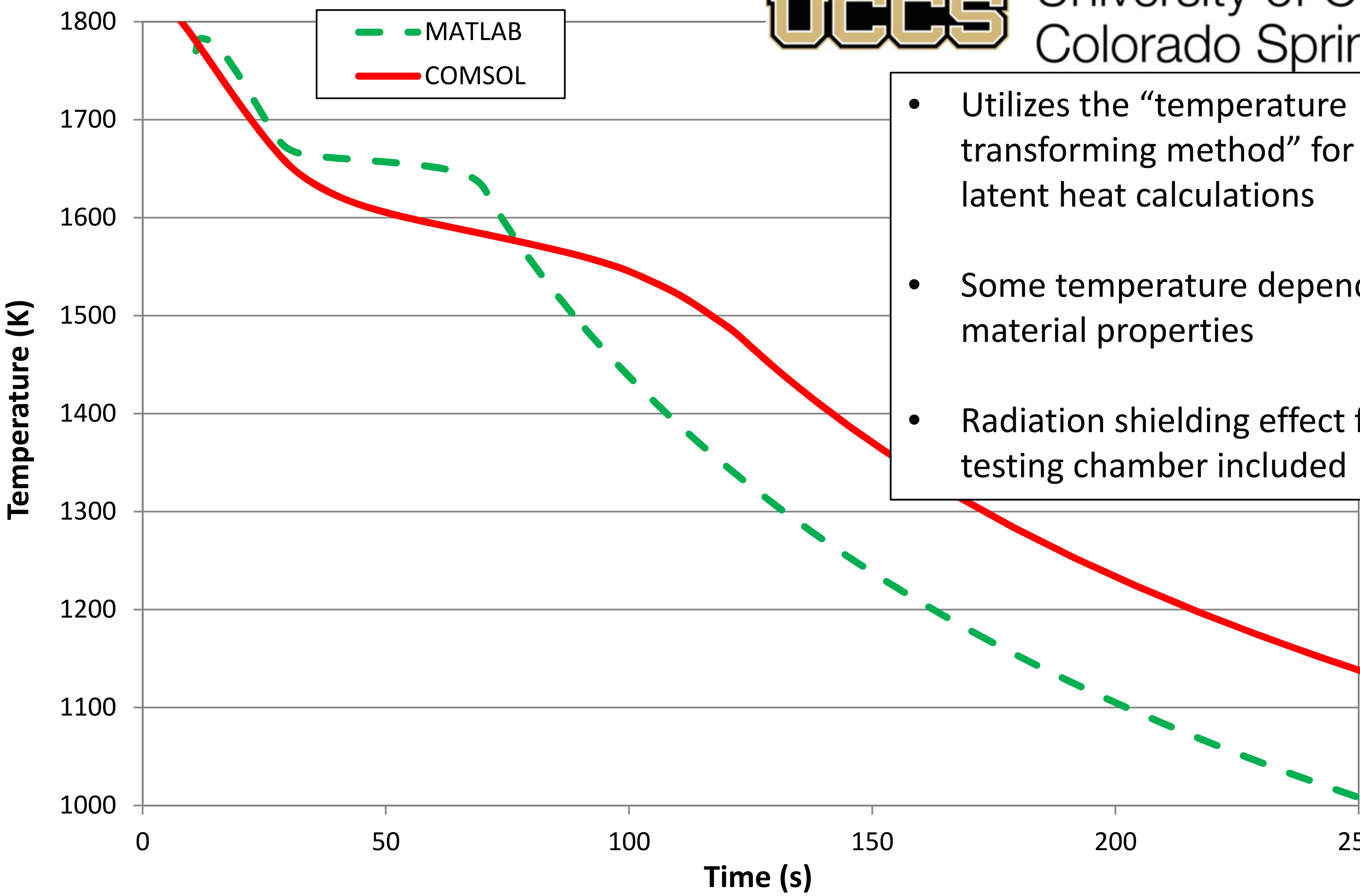


- 2D Axisymmetric about θ
- Radiation and convection boundary conditions
- Neglects PCM density change and void formation
- Latent heat handled by the “enthalpy method”

Predictive Modeling



Predictive Modeling



- Utilizes the "temperature transforming method" for latent heat calculations
- Some temperature dependent material properties
- Radiation shielding effect from testing chamber included

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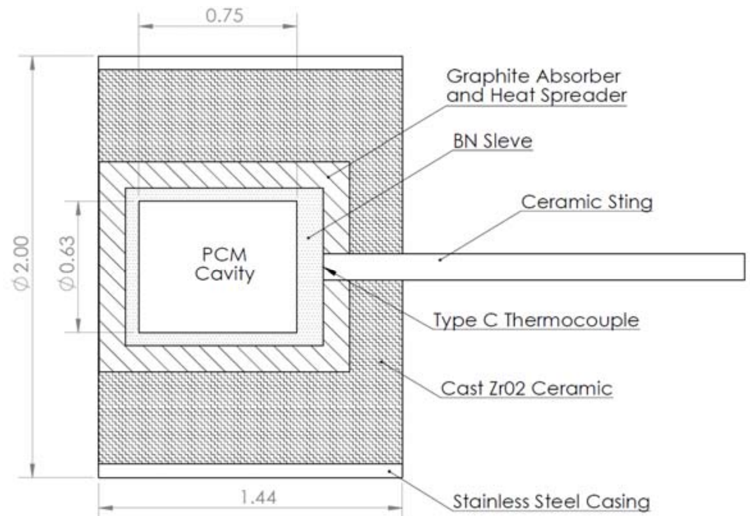
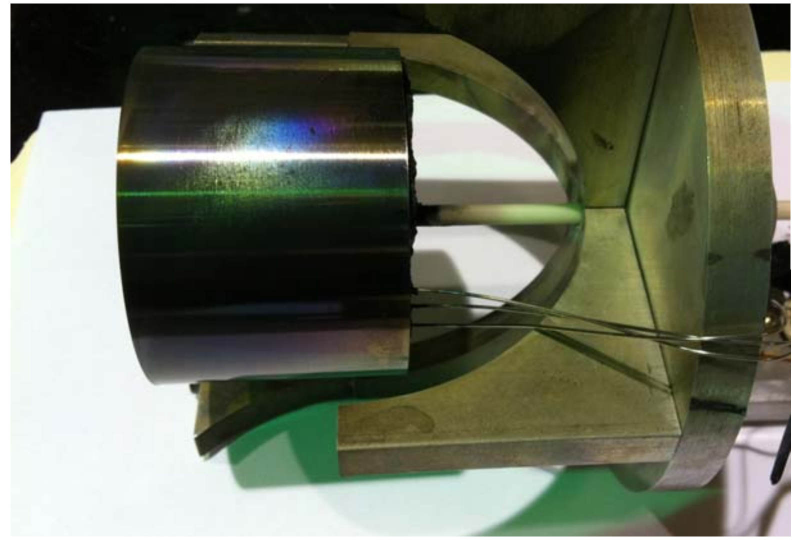
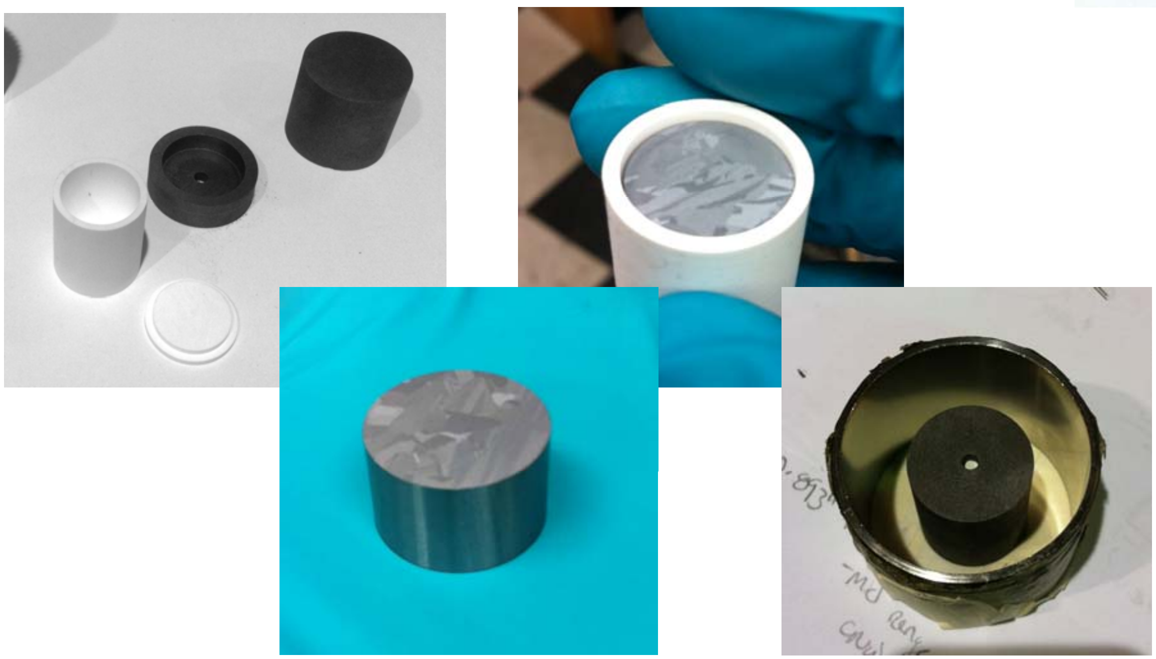
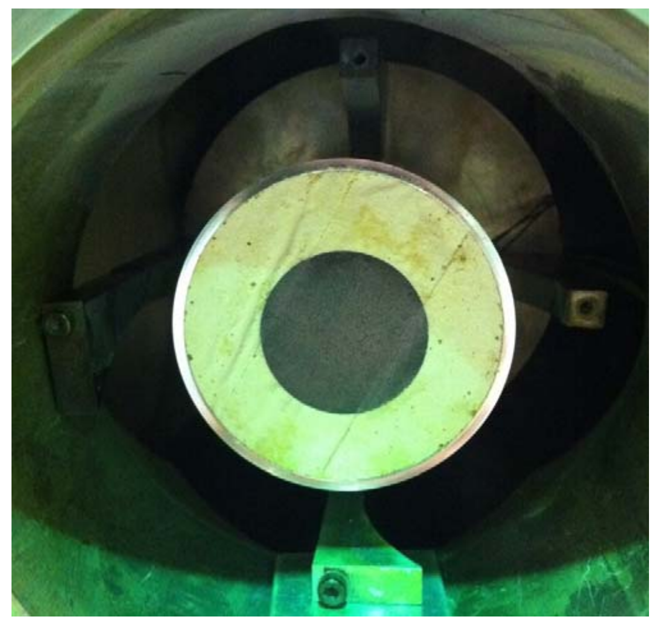
Experimental Testing









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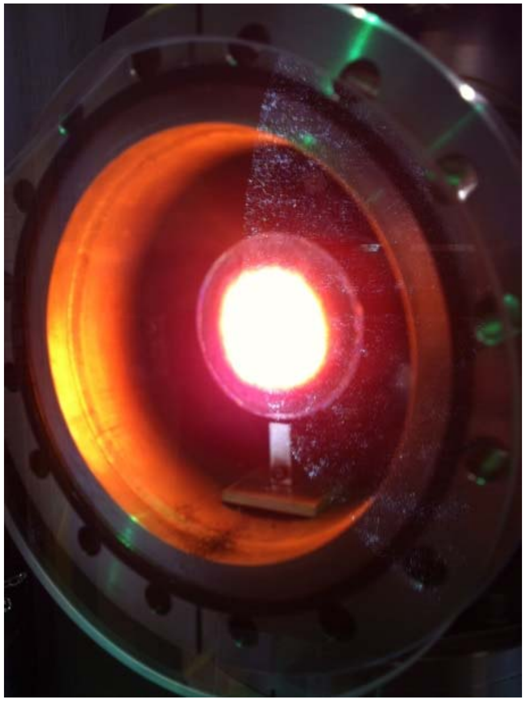
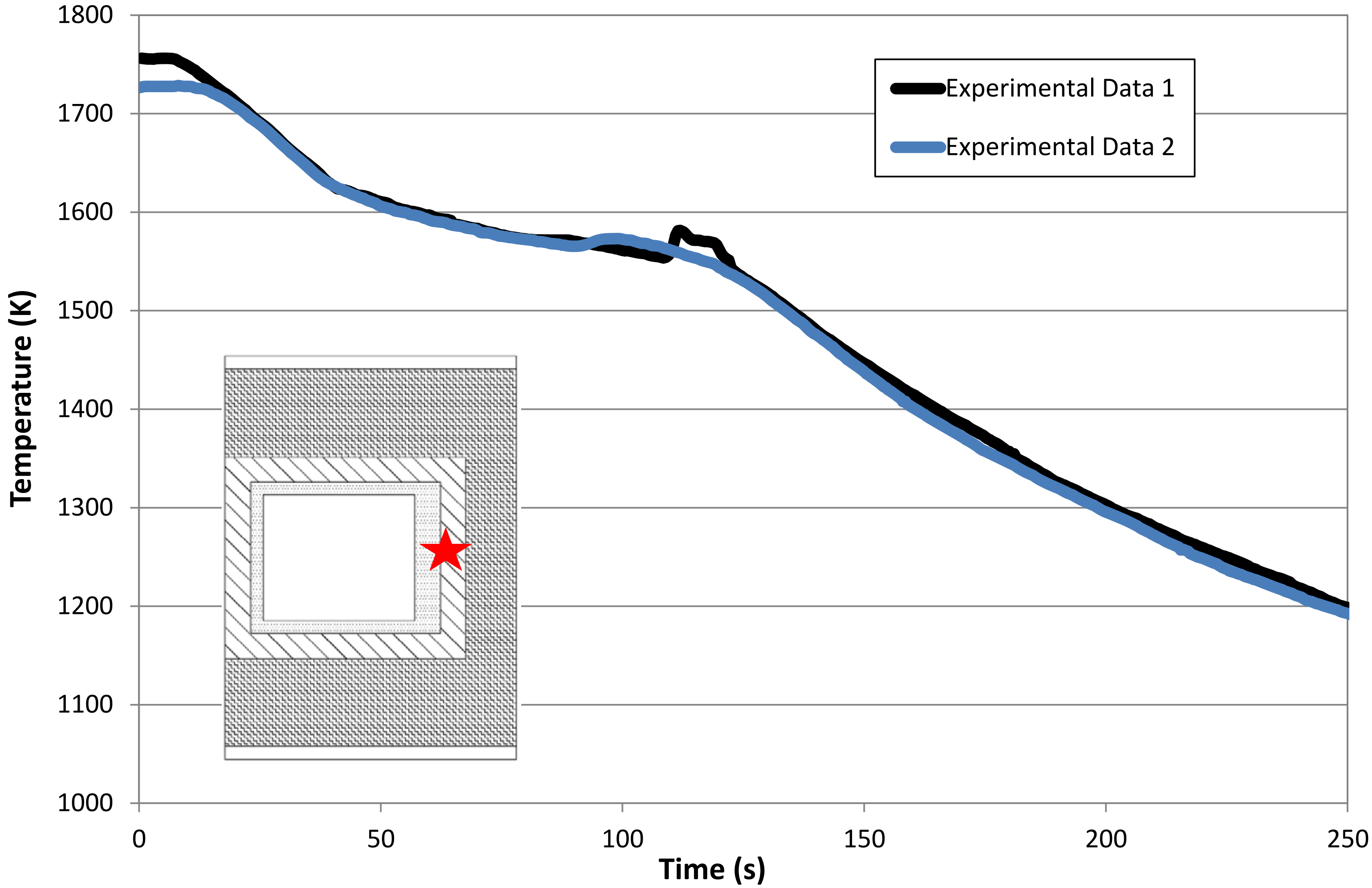
Experimental Testing

Testing Procedure

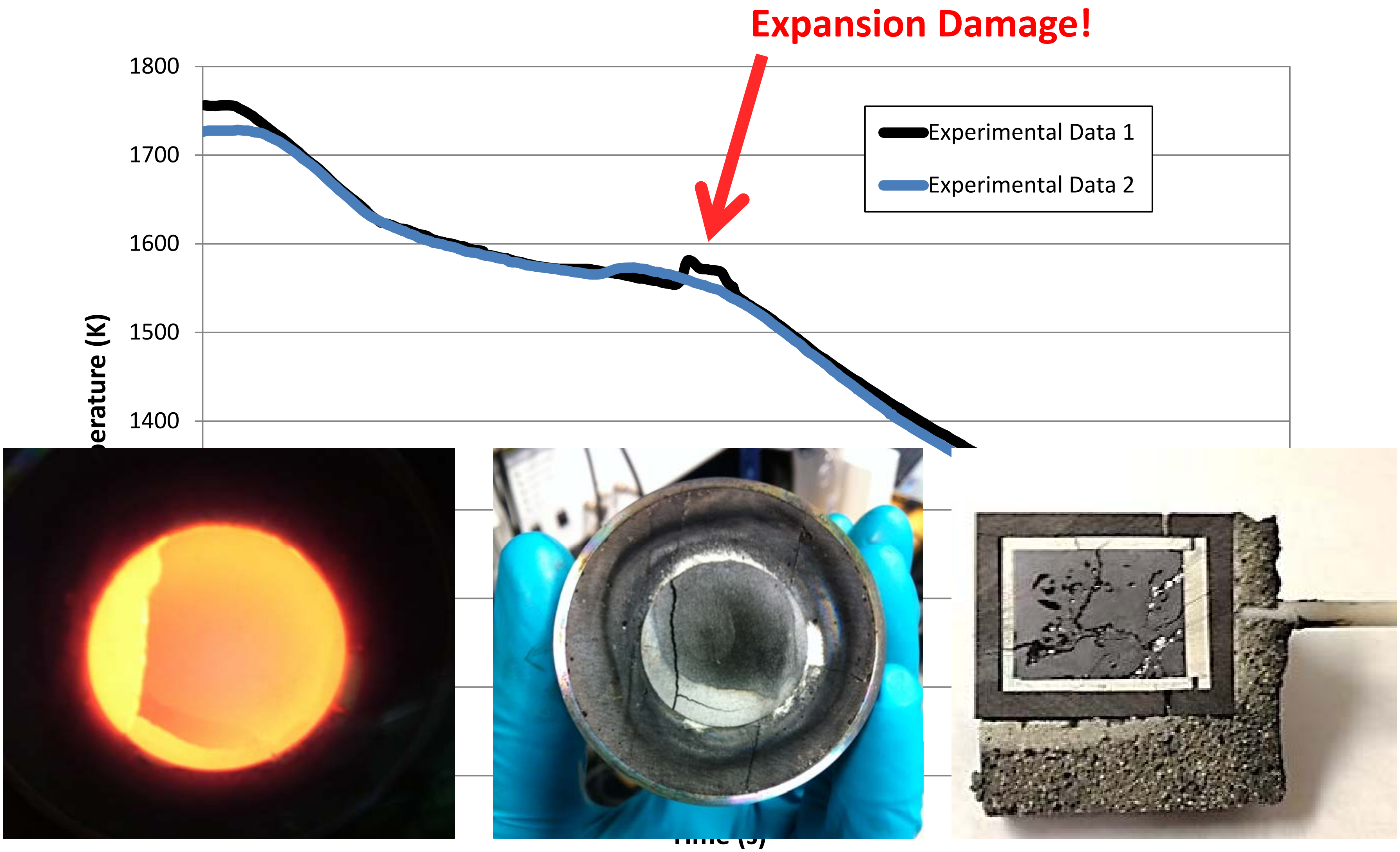
- Bake out at 300 °C using 1000 W spot lamp, at 30 mTorr to evaporate "proprietary water based binder" in the cast ZrO_2 ceramic
- Evacuate to 30 mTorr at ambient temperature, then heat "on-sun" to 300 °C to ensure no gas is trapped in the test section prior to seal tightening due to thermal expansion
- Fill chamber with 150 Torr of Argon
  - Required to suppress $Zr0_2$ + C reaction
  - Prevents irreparable damage to quartz chamber window
- Gradually increase power until thermal equilibrium is achieved
- Use "shutter curtain" to quickly cut power and record cooling curve



Experimental Data



Experimental Data



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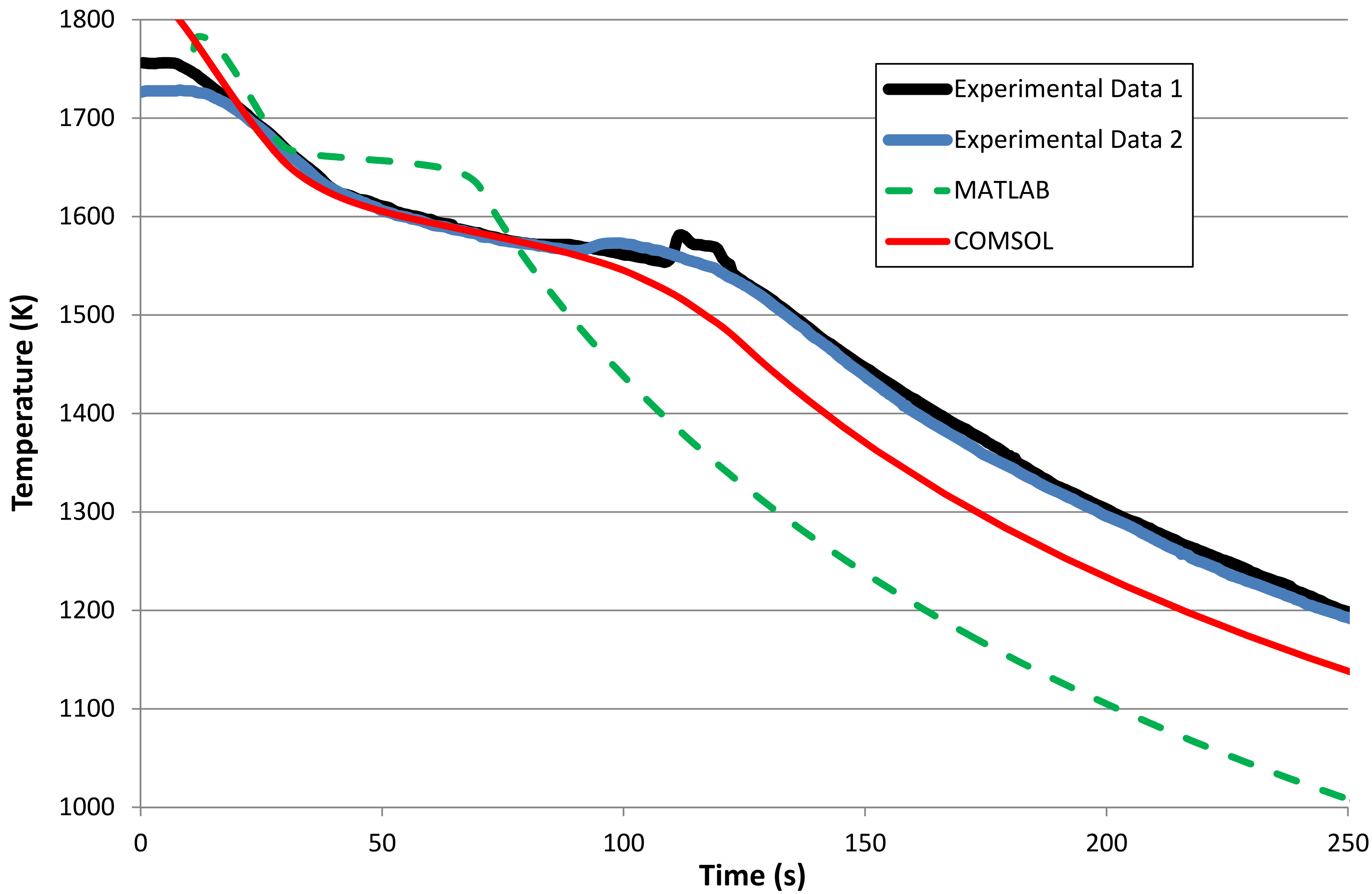
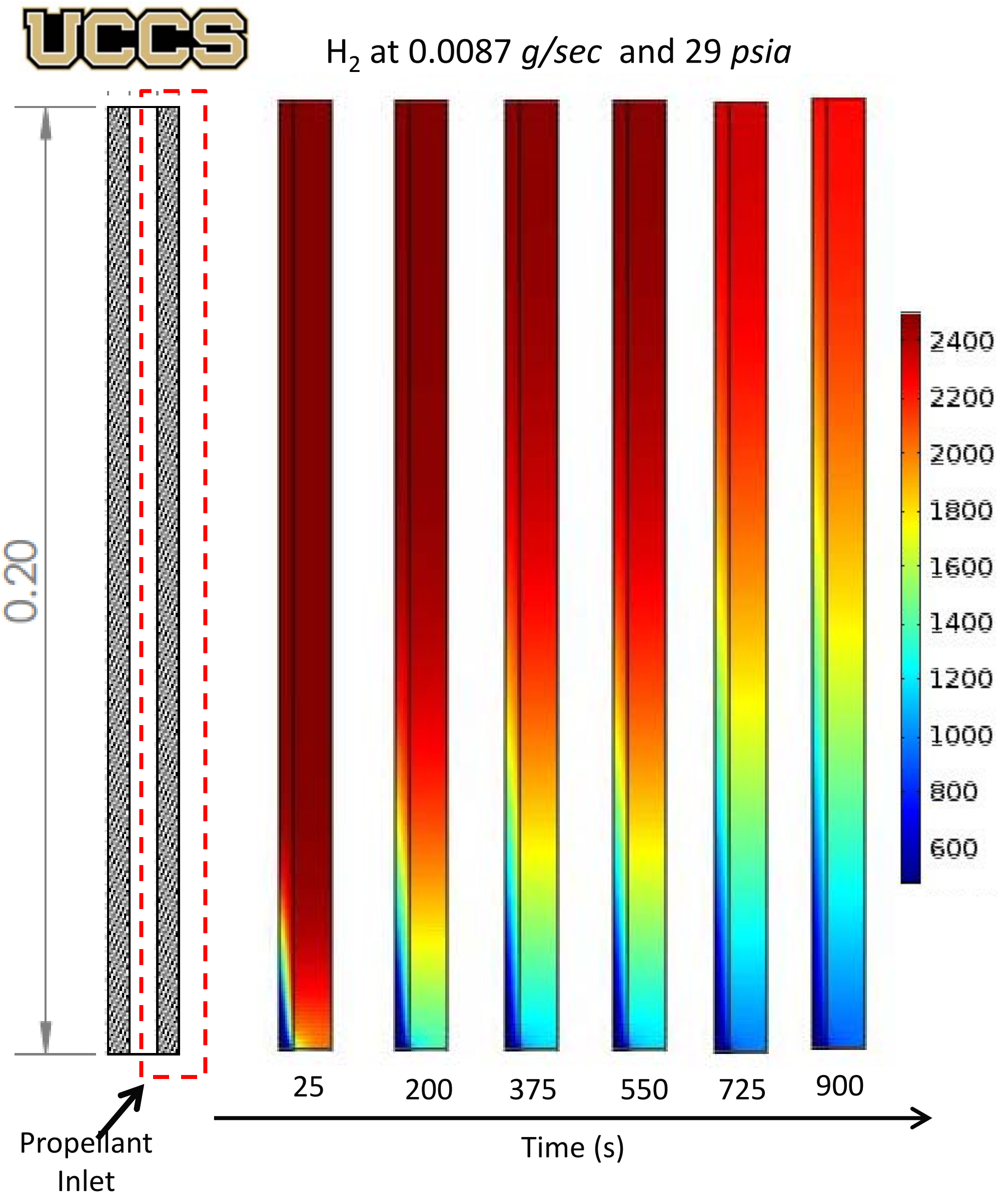
Data Comparison



Future Work

Convective Coupling

- The ISUS system was capable of maintaining a constant temperature with a sensible heat medium due to “extra length” being designed into the heat exchanger
- The design spec of the ISUS RAC has the potential for 0.72 MJ/kg with a 600 K ΔT (double the original design spec)
- In reality, achieves 0.46 MJ/kg if the steady output region is considered “usable”
- To date, no discussion of latent heat thermal energy storage discusses **advantageous convective coupling**
- Will use commercial multi-physics software (Star-CCM+) to replicate a ISUS heat exchanger channel and switch storage to latent heat
- Seek a quantification of convective coupling benefit

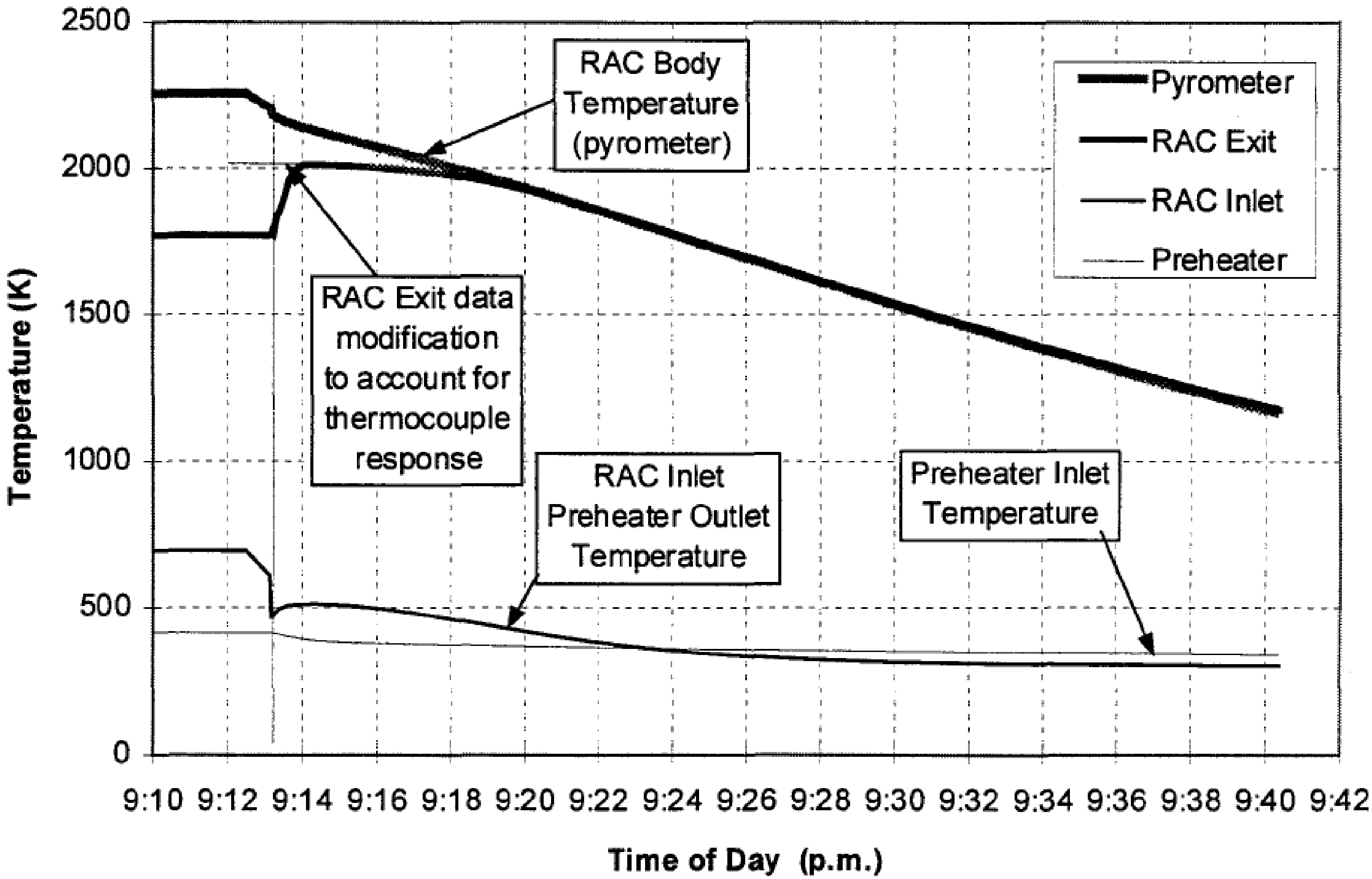


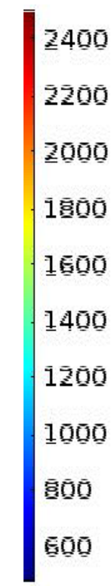
Convective Coupling

UCCS

H_2 at 0.0087 *g/sec* and 29 *psia*

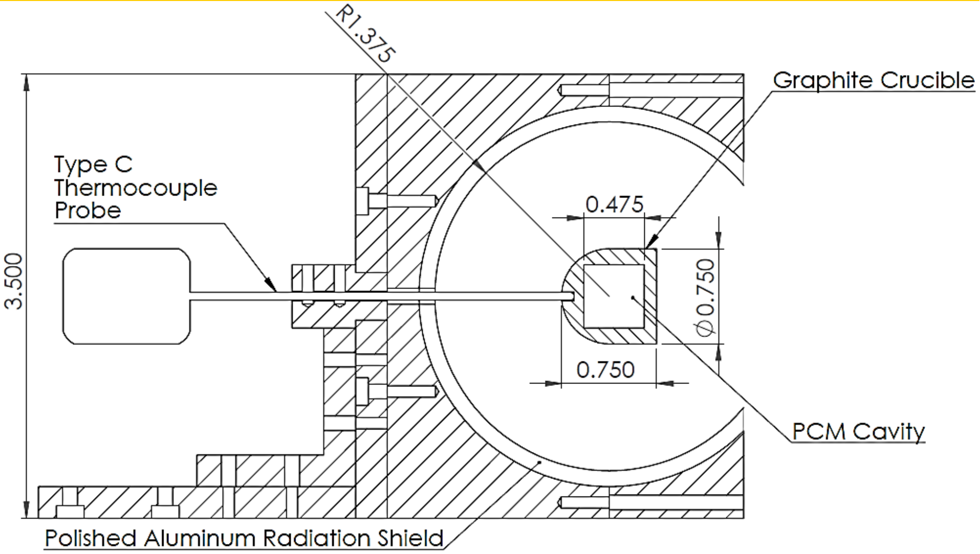
- The l cons med into
- The potε the c
- In re outp
- To da ener **conv**
- Will (Star chan
- Seek benefit

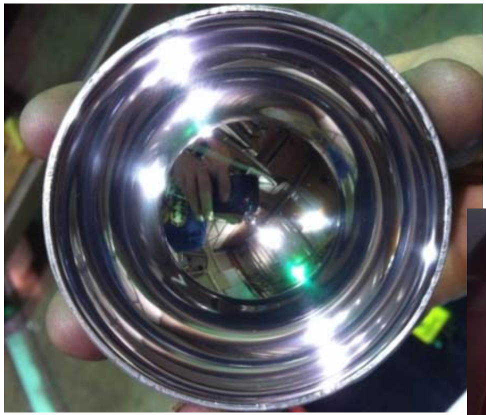




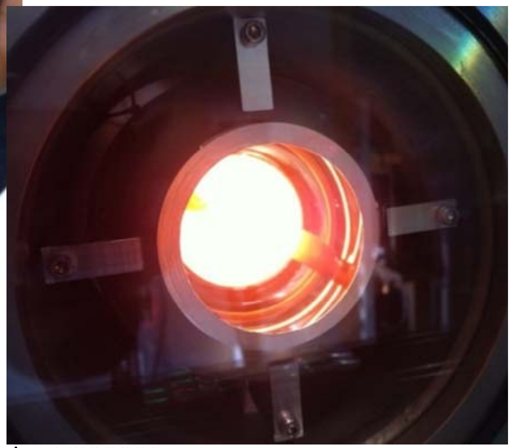
Radiation Shielding

- Radiation shielding will be required to increase molten silicon yields
- Testing was performed with spherical radiation shields during solar furnace development
- Goal was to reproduce results published by Steinfeld and Fletcher – found that assumptions of iso thermal test sections were inaccurate
- Demonstrated shielding efficiency of approx. 55% with hand polished aluminum shields
- Must be integrated into predictive models
- Ray tracing code from AFRL has been written to produce point to point view factors for spherical and cylindrical geometries





$$T_{Max} \approx [\ldots]\left(\frac{1}{1-\eta_{Shielding}}\right)^{1/4}$$



Project Conclusion

- Emulate an ISUS heat exchanger channel and experimentally demonstrate sensible and latent heat storage options

- Requires increasing furnace performance and insulation techniques
  - Replacement of heliostat mirrors will yield a 30% power increase
  - Secondary concentrator can increase c. ratio to > 10,000:1
  - Addition of radiation shielding and potentially CBCF insulation

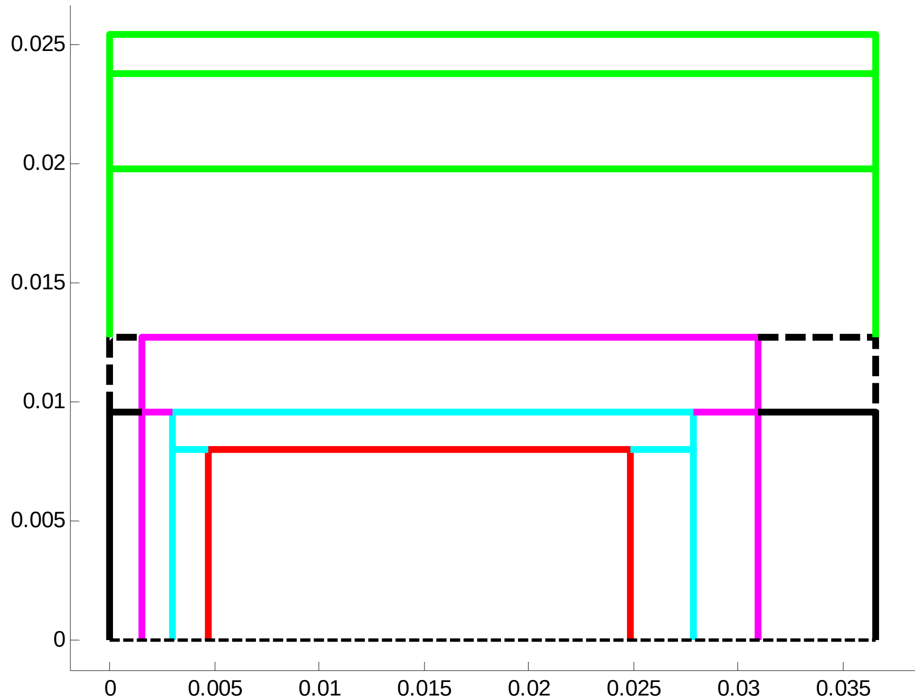
- When complete, experiments will bring latent heat thermal energy storage for STP to a similar TRL level as sensible heat options

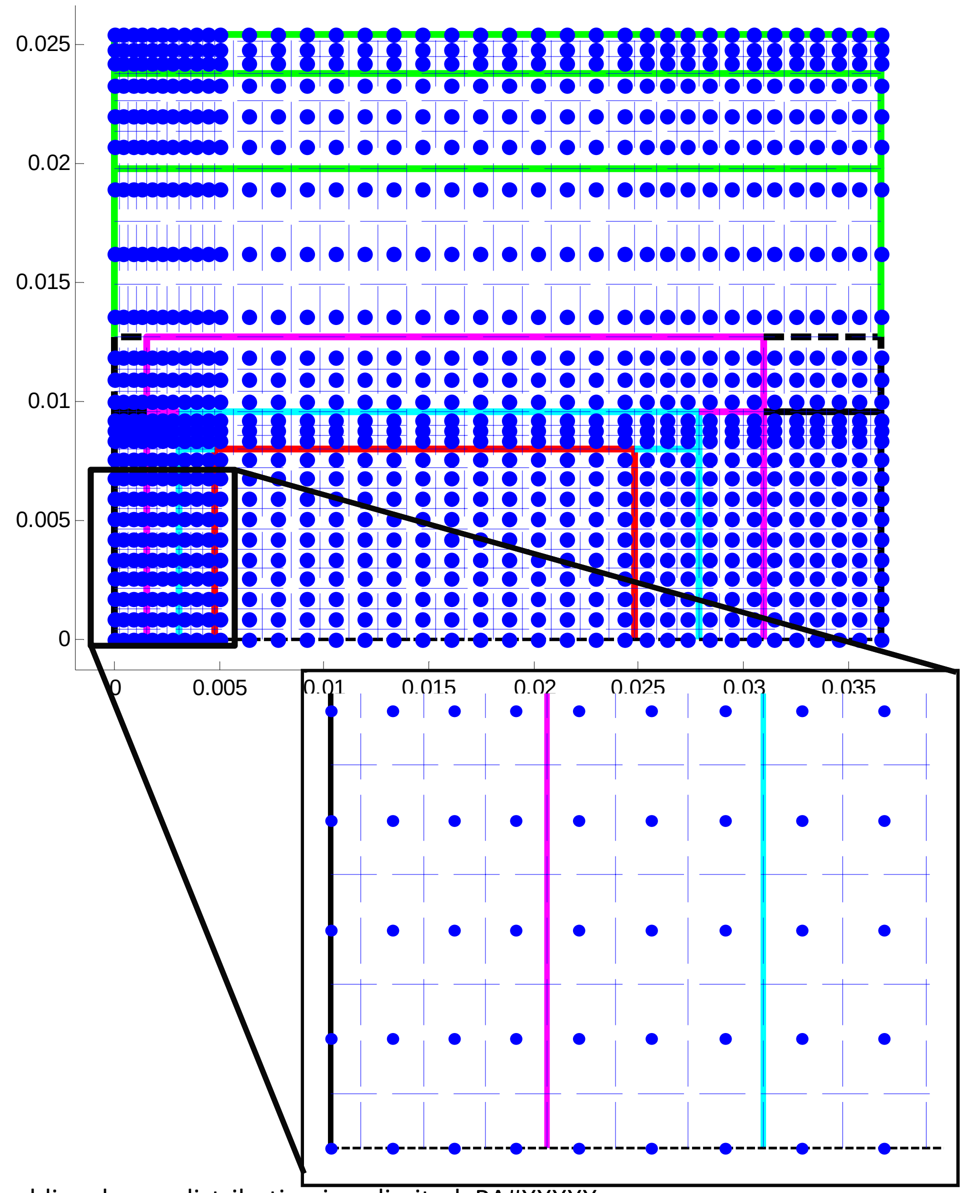
- This research is the most through investigation into high temperature latent heat thermal energy storage and will provide a road map for future solar thermal system designers

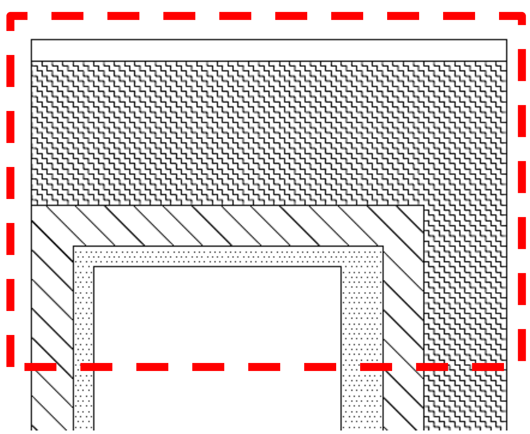
Supplemental Slides

...

MATLAB Model







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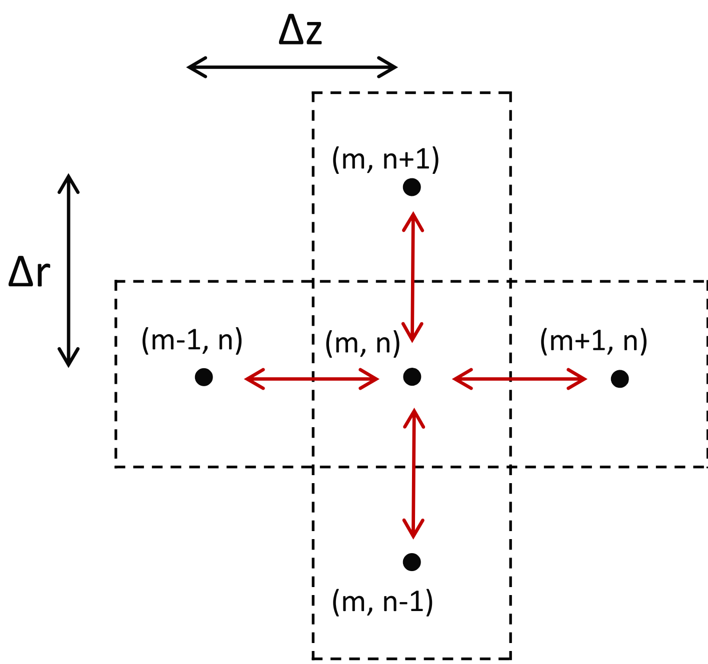
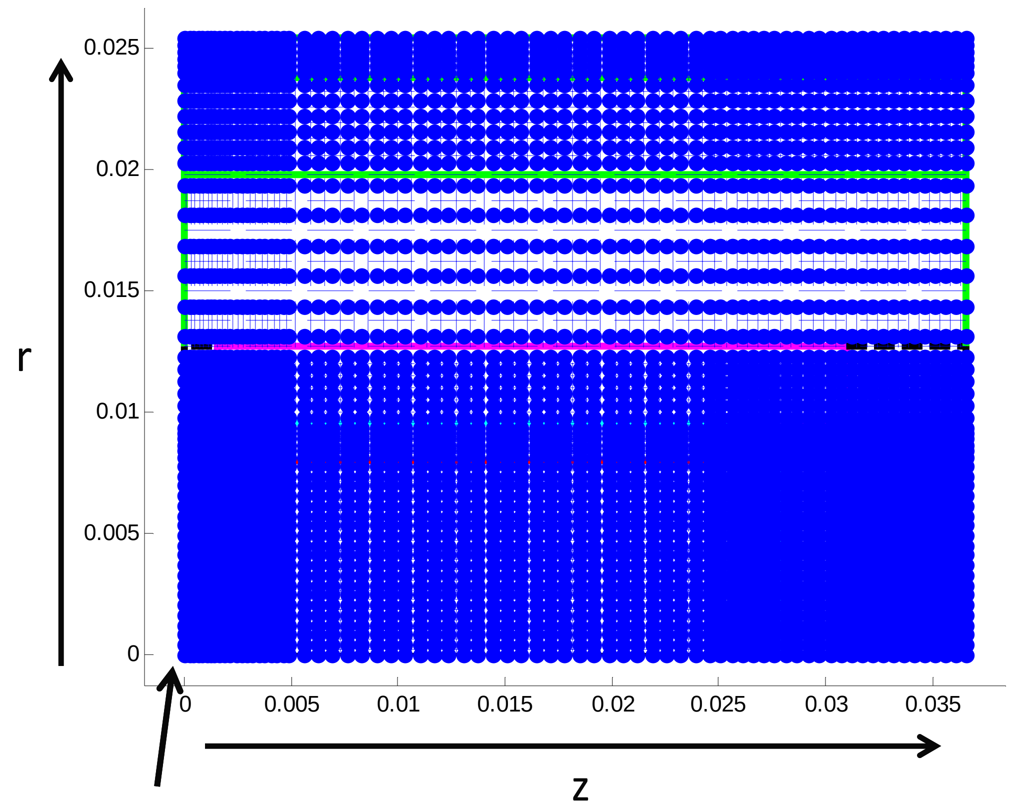
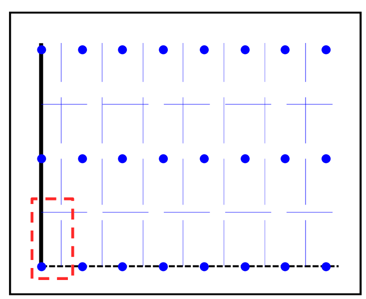
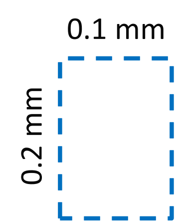
MATLAB Model

- 3700 Nodes
- dt = 0.00025 seconds
- Approx. 14 hours runtime for a 300 second simulation





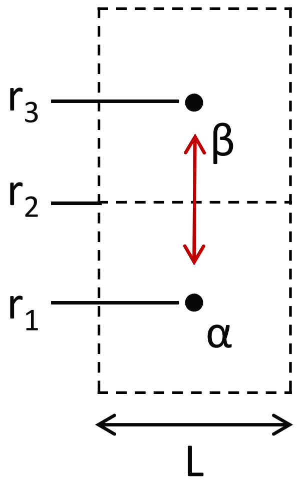




V = 1.3×10^{-5} cc
m = 2.65×10^{-5} g

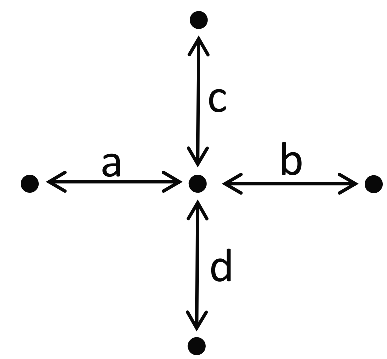
MATLAB Model

Conduction in the "r" Direction

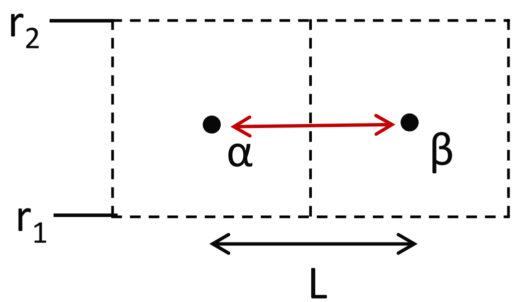


$$q = \frac{\left(T_\beta - T_\alpha\right)}{\dfrac{\ln\left(r_2/r_1\right)}{2\pi L k_\alpha} + \dfrac{\ln\left(r_3/r_2\right)}{2\pi L k_\beta}}$$

All geometric terms are offloaded into coefficient matrices to speed computations



Conduction in the "z" Direction



$$q = \frac{A\left(T_\beta - T_\alpha\right)}{L\left(1/k_\alpha + 1/k_\beta\right)}$$

$$A = \pi\left(r_2^2 - r_1^2\right)$$

At Each Time Step

$$q_{net} = q_{left} + q_{right} + q_{down} + q_{up}$$

$$\Delta T = \frac{q_{net}\,dt}{mc_p}$$

Node With PCM

$$\Delta T = \frac{q_{net}\,dt}{mc_p} + LatentHeat(rr, zz)$$

MATLAB Model

Radiation Boundary Condition

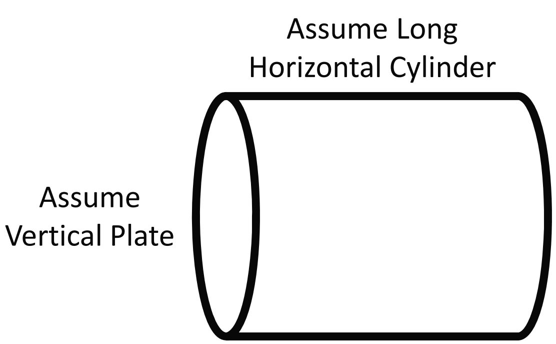
$$q_{rad} = -\sigma \varepsilon A\left(T_{node}^4 - T_{amb}^4\right)$$

$$q_{net} = q_{left} + q_{right} + q_{down} + q_{up} + q_{rad} + q_{conv}$$

$$\Delta T = \frac{q_{net}\,dt}{mc_p}$$

Convective Boundary Condition

$$q_{conv} = -hA\left(T_{node} - T_{amb}\right)$$



Vertical Plate → h ≈ 6.7 (W/m²K)

$$\mathrm{h} = \frac{k}{L}\left(0.825 + \frac{0.387\mathrm{Ra}_L^{1/6}}{\left(1 + (0.492/\mathrm{Pr})^{9/16}\right)^{8/27}}\right)^2$$ *(Churchill and Chu)*

Assume laminar flow with Argon at 500 *K* and 150 *Torr* *($Ra_L = 10^6$)*

Horizontal Cylinder → h ≈ 5.7 (W/m²K)

$$\mathrm{h} = \frac{k}{D}\left(0.6 + \frac{0.387\mathrm{Ra}_D^{1/6}}{\left(1 + (0.559/\mathrm{Pr})^{9/16}\right)^{8/27}}\right)^2$$ *(Churchill and Chu)*

Assume laminar flow with Argon at 500 *K* and 150 *Torr* *($Ra_L = 10^6$)*

Pointing Error Calculations

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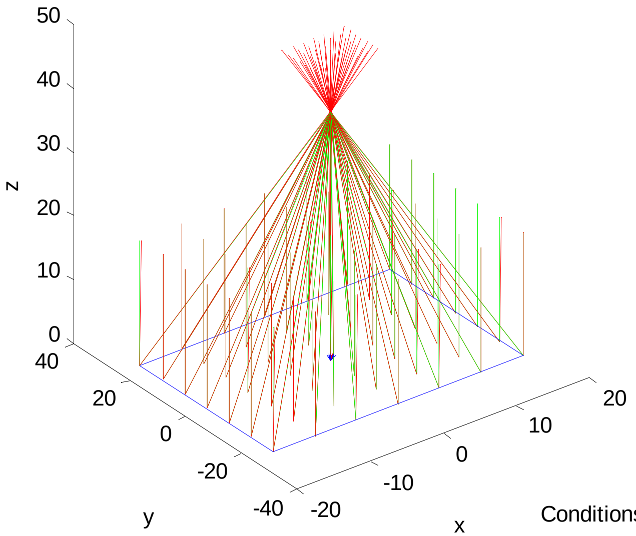
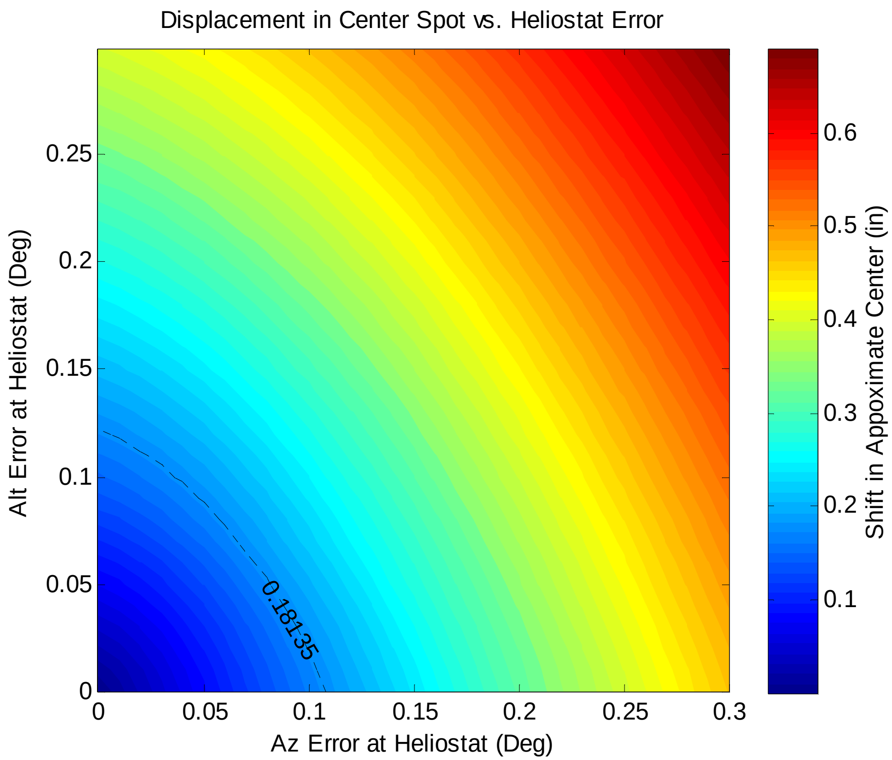
Accuracy Requirements in the Literature

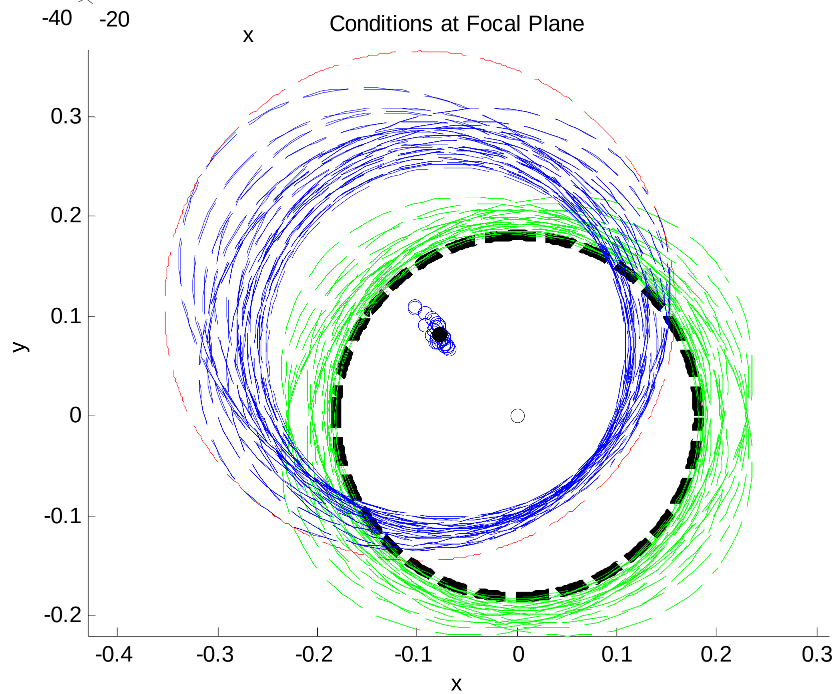
- ± 0.3° - *Hukuo 1957*
- ± 0.1° - *Ethridge 1979*
- ± 0.5° - *Holmes 1995*
- ± 0.1° - *Kennedy 2004*



Note idea image for a parabolic concentrator

$$d = 2f\sin(\theta_{sun}/2)$$

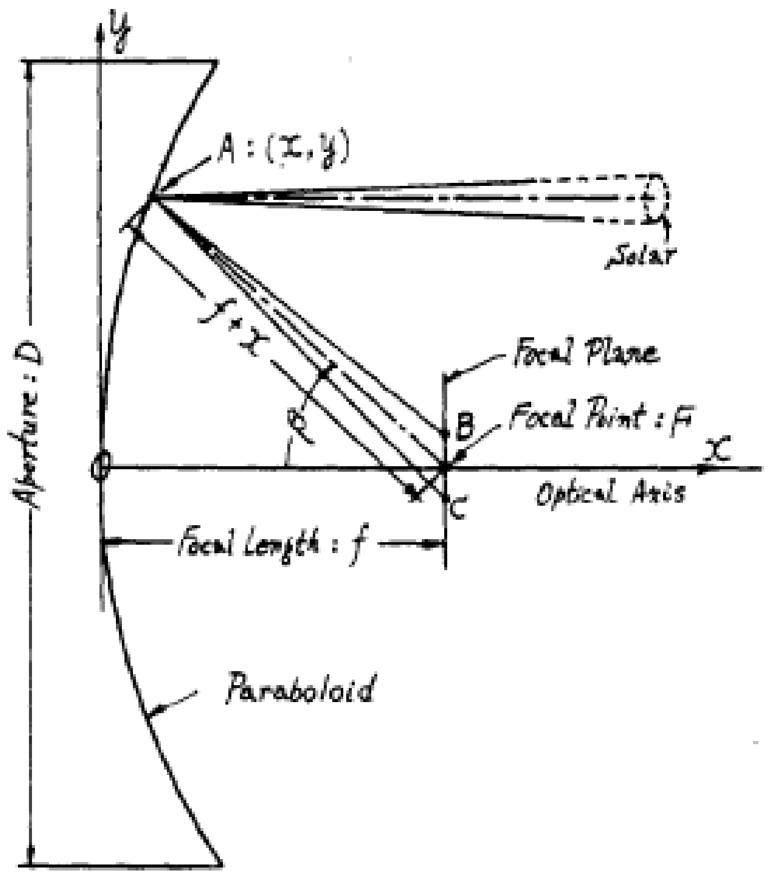




Pointing Error Calculations

Hukuo and Mii 1957

FIG. 1 — Section of a parabolic mirror.



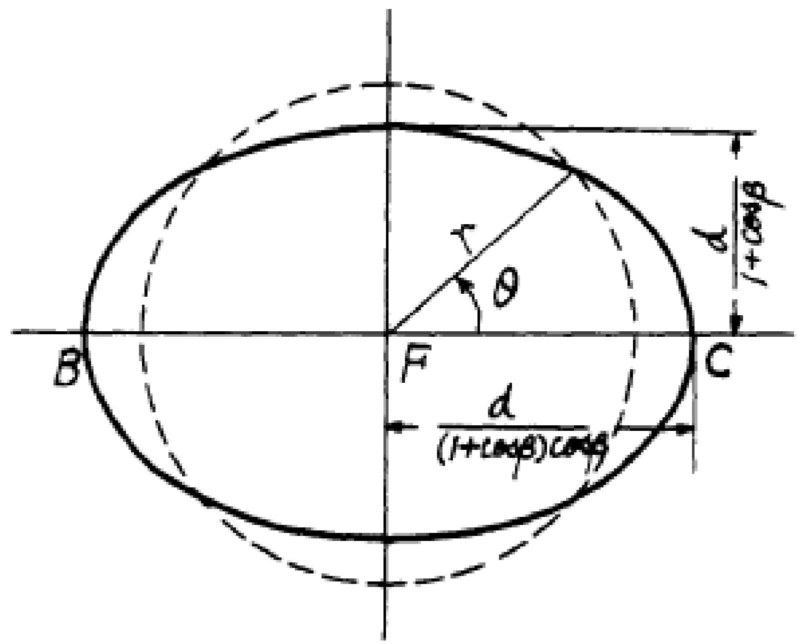
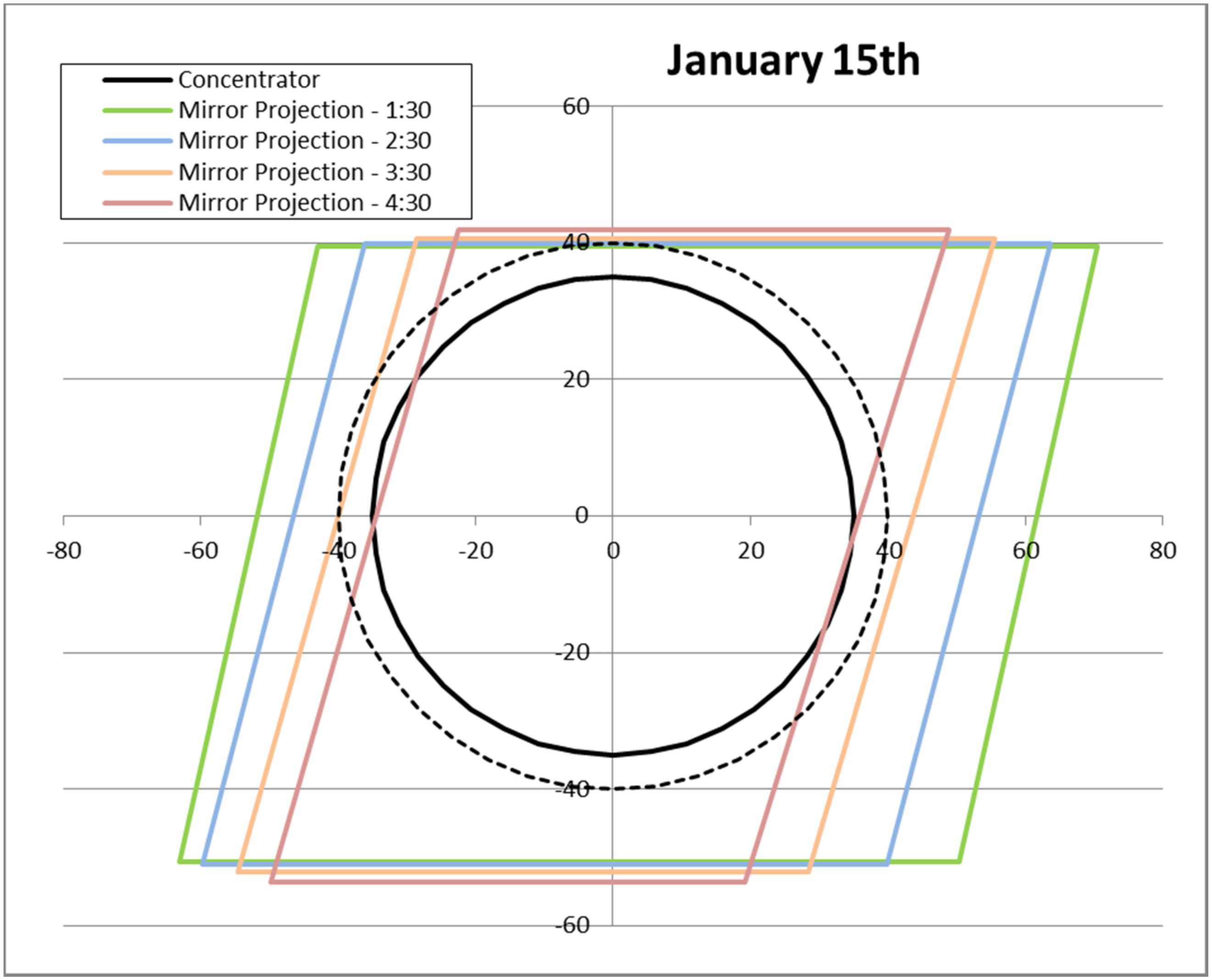


FIG. 2 — Solar image produced by a ray which is reflected by the paraboloid with the angle β.

Heliostat Coverage



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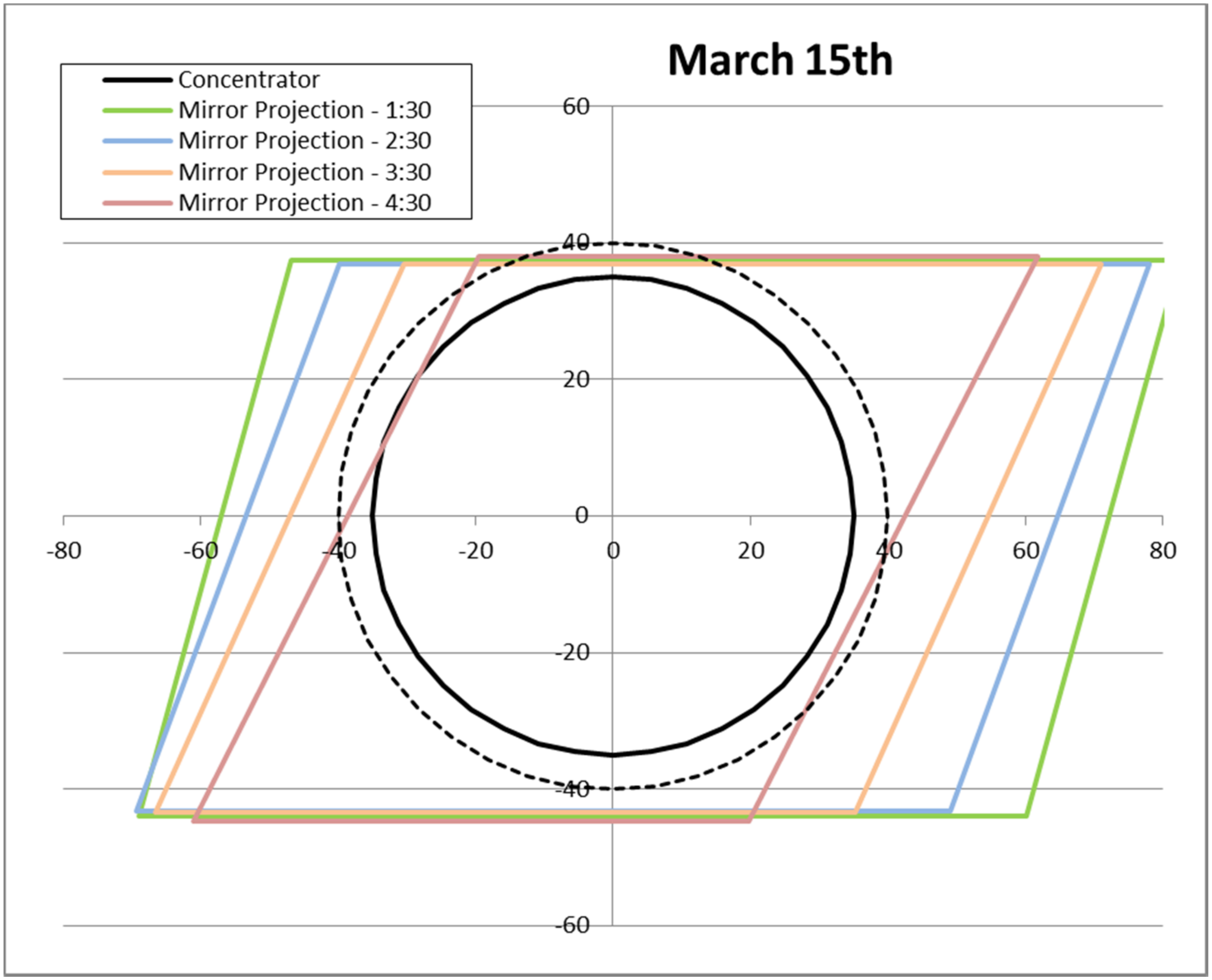
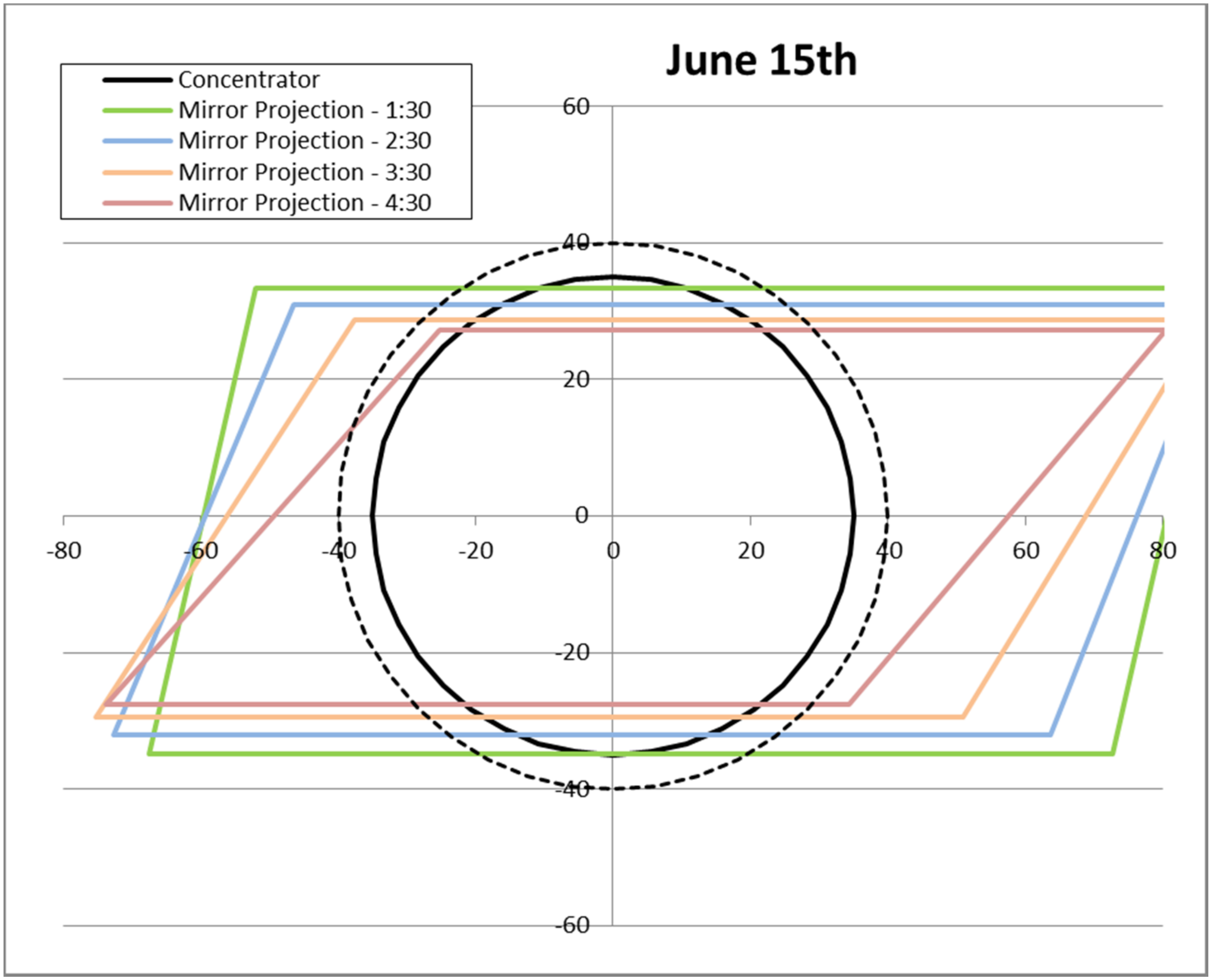
Heliostat Coverage



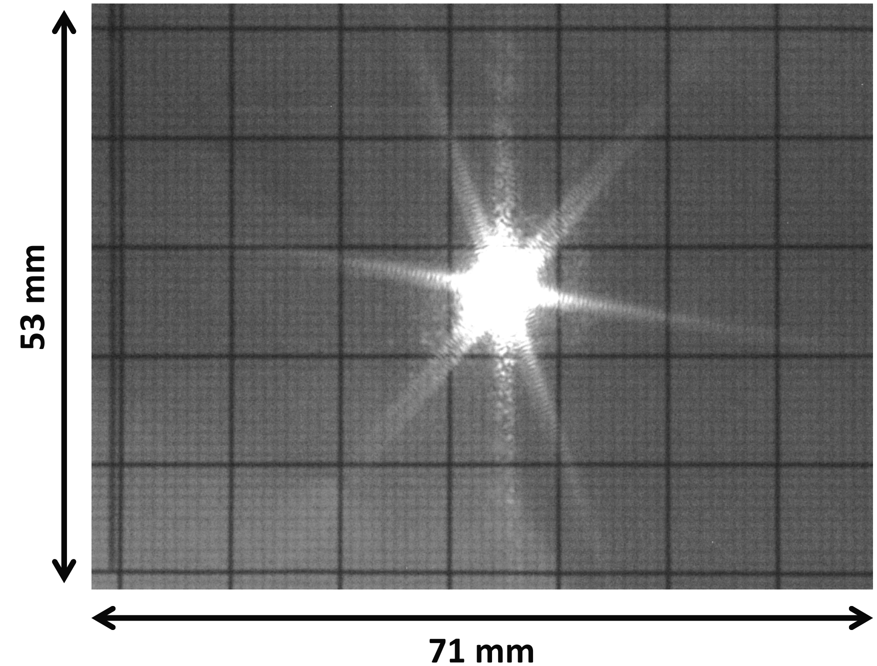
Heliostat Coverage



DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited. PA#XXXXX

CCD Diagnostic Method

- Read pixel intensities from CCD after subtracting representative "dark frame"
- Convert using black body calibration from *counts/μs* to W/m^2nm at 980 *nm*
- Account for reflectivity of pseudo-Lambertian surface
- Convert from W/m^2nm to *# of Suns*
  - Weight against filter band pass
  - Use ASTMG173 data to scale 980 *nm* values with the full spectrum
  - Multiply by ASTMG173 standard insolation to get pixel reading in W/m^2
- Compare to locally measured insolation to get map of concentration ratios



Sony ICX445 CCD - 1.2 MP

16-bit mono output format

Images captured at 640 x 480

Tech Comparison Metrics

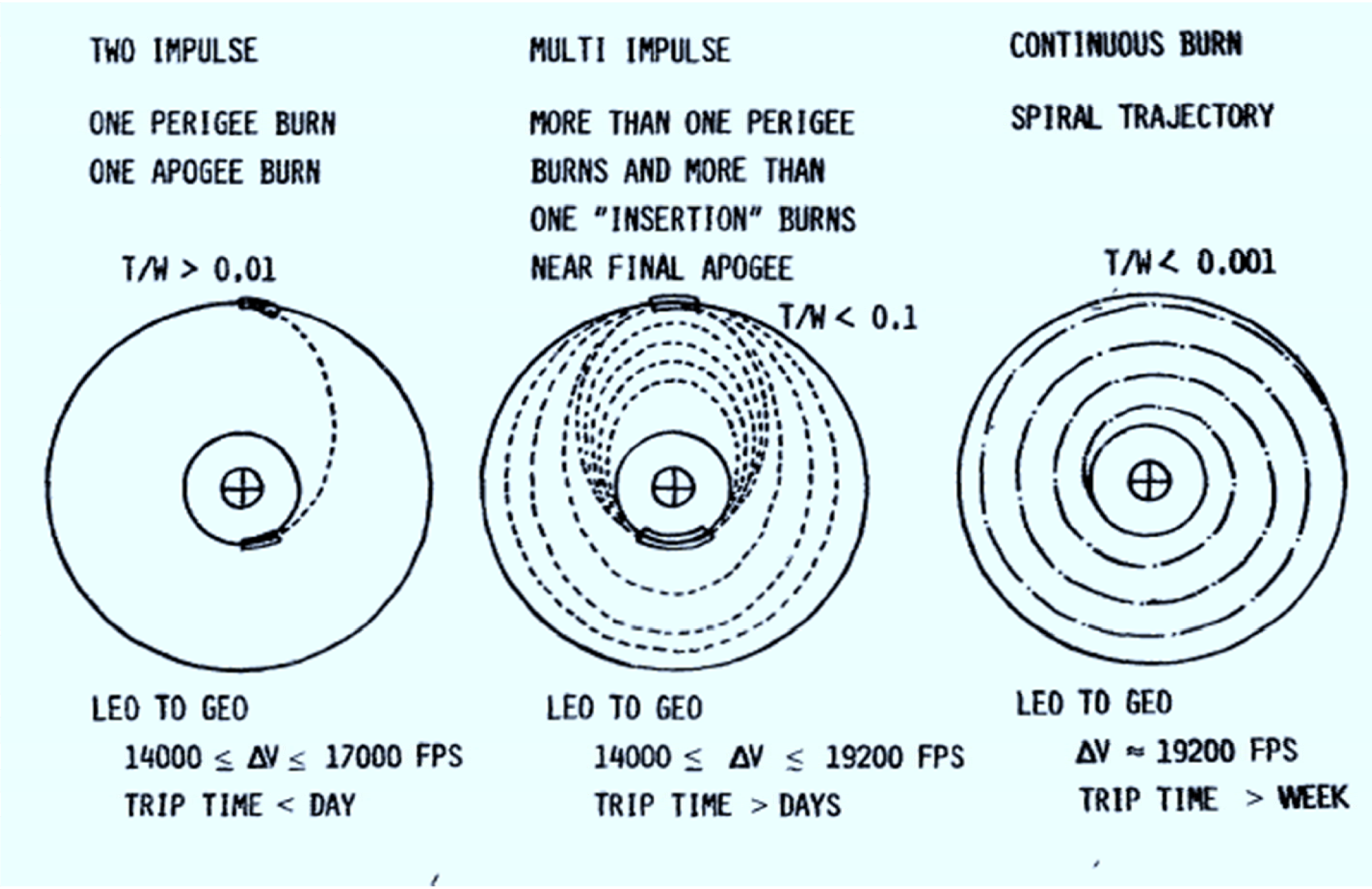
Solar Thermal w/o Energy Storage	Chemical Thrusters	Electric Propulsion
• Eliminated PCM and TPV • Reduced solar collector size • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV	• Astrium Hydrazine Monoprop • Commercially available 1 N and 20 N models • Isp: 220-230 s • Removed thermal energy collection and storage system • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV	• XHT-100 Hall Effect Thruster • 95 W power draw • Isp: 750-1000 s • 3 – 10 mN Thrust • Removed thermal energy collection and storage system • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV

Identical Mass Fractions ($M_{Propulsion\ \&\ Power}$ = 58%)

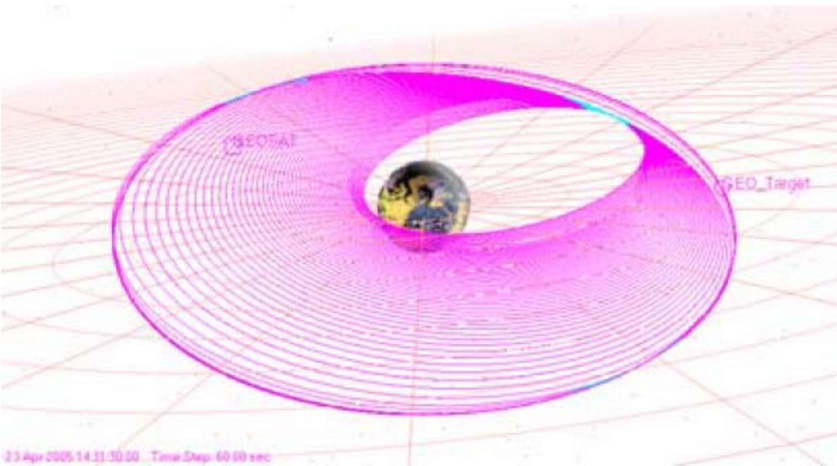
Total ΔV and Delivery Time are Primary Comparison Metrics

USC Viterbi School of Engineering

Ethridge Orbit Calculations



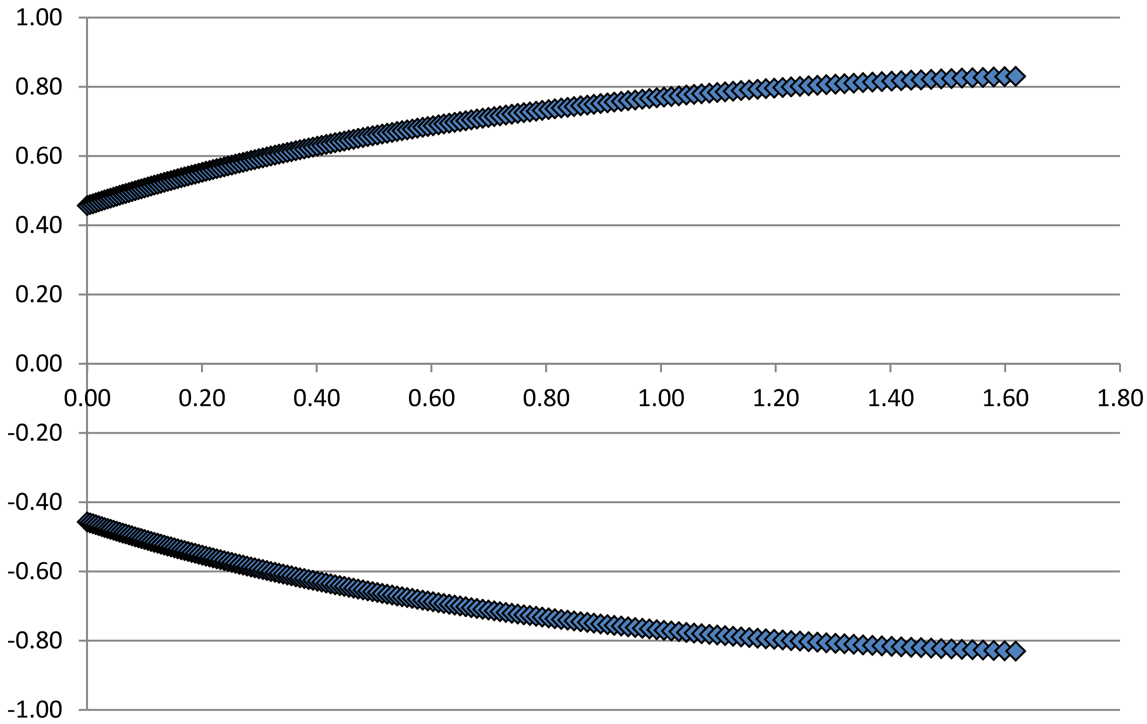
Kennedy Orbit Calculations



- 10% "On Time"
- 100 kg satellite
- Launch from Ariane 5 into GTO (350 x 35,717 km - 7°)
- Transfer to 0° at 116 °E
- Assumes ½ N thrust and 400 s I_{sp}
- 48 kg for *JUST* solar thermal engine and propellant

Start Date	1 April 2005, 00:00:00.00 (Julian Date 2453461.5)
End Date	6 May 2005, 09:11:16.96 (JD 2453496.88)
Elapsed Time	35 days, 9 hrs., 11 min.
Number of Maneuvers	58 (51 apogee kicks, 7 plane changes at node crossings). Two-orbit "hold" of 42 hrs., 20 min. introduced after apogee kick 48 to attain proper orbital phasing at GEO
Total Velocity Change	1,761 m/s
Propellant Consumption	36.184 kg
Final Mass	63.816 kg
Engine "On-Time"	80 hrs., 33 min.

Secondary Concentrator



- Defined by parametric equations given by *Welford and Winston 1978*
- CAN NOT be used to increase power due to low f/d ratio for the concentrator
- CAN be used to increase concentration ratio

Diameter	Max Angle	Minimum Diameter	% Area Increase	Max Ratio	Minimum Spot	Spot Change	**C Ratio Change**
70	33.0	1.66	0%	3.24	0.914	0.84	5%
75	35.162	1.81	15%	2.99	1.046	1.09	-16%
80	37.7	2.09	32%	2.67	1.220	1.49	-29%

Ammonia and Hydrazine

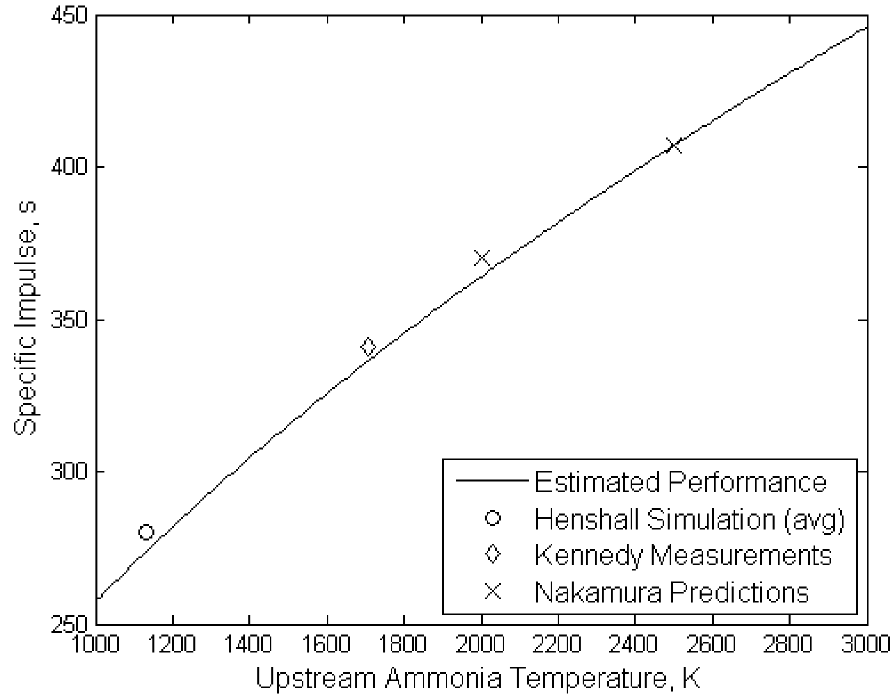
$3N_2H_4 \rightarrow 4NH_3 + N_2$ - 336 kJ

$4NH_3 \rightarrow 2N_2 + 6H_2$ + 184 kJ

Net 1.6 MJ/kg

α_D	Isp
0	253
0.2	274
0.4	289
0.8	312
1	322

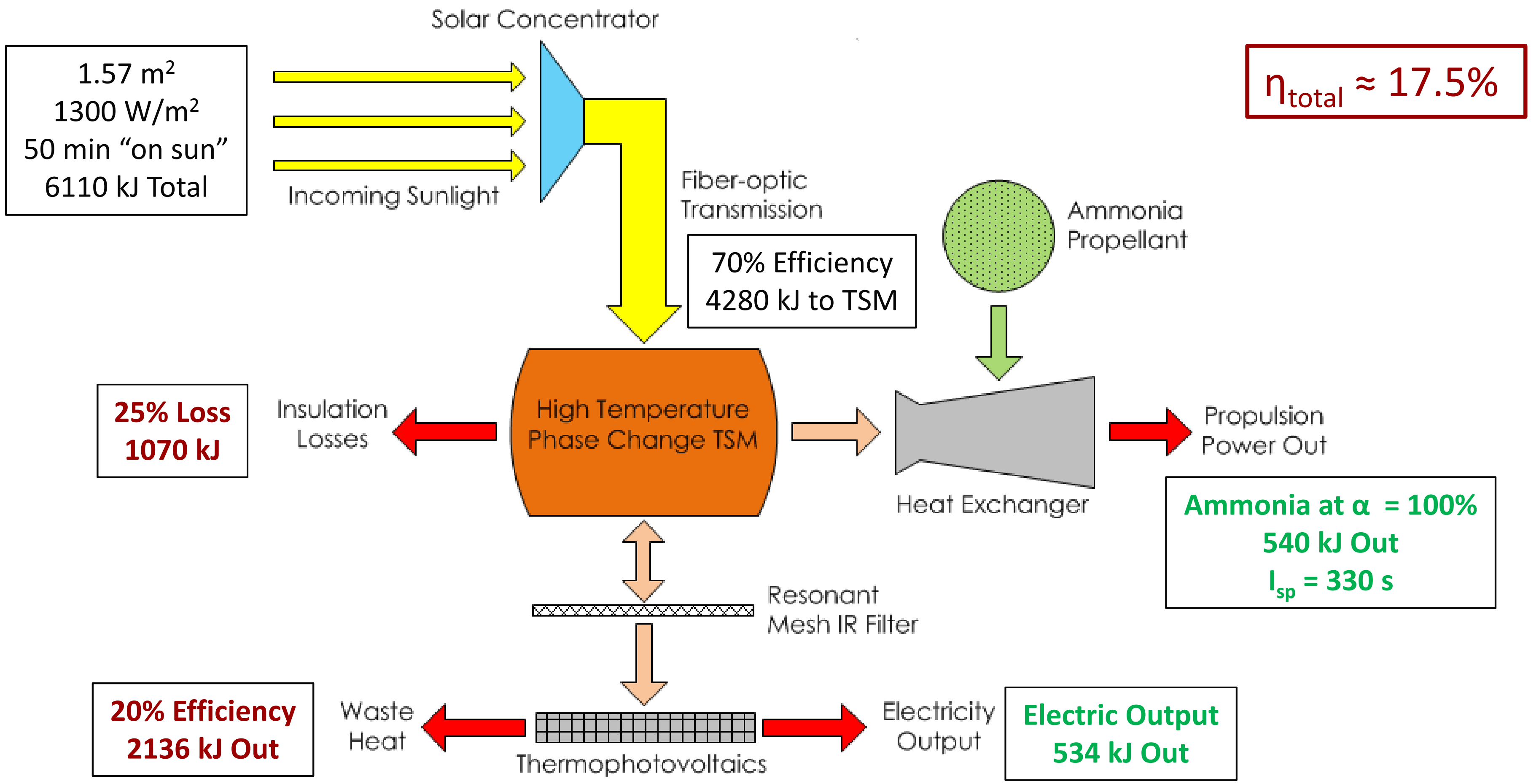
- Incomplete dissociation will lower performance
- Equilibrium calculations for 1500 K solar thermal thruster (*Colonna et. al. 2005*)
- Note, hydrazine thrusters typically have $\alpha_D \approx 55\%$



$$V_e = I_{sp} g_o = \sqrt{\frac{T_o R}{\mathrm{M}} \frac{2\gamma}{\gamma - 1}\left[1 - \left(\frac{p_e}{p_o}\right)^{(\gamma-1)/\gamma}\right]}$$

Energy Values

For each 200 km Orbit



Tech Comparison Metrics

- Satellite is sized for a 200 km circular orbit
  - Storage sized for approx. 36 min eclipse
- Assumes 20% total electrical system efficiency
- Assumes 70% thermal collection efficiency
- Approximates impulsive burn profile with a 5% firing rule